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THESIS

ESTIMATING PRODUCTION COST WHILE LINKING COMBAT SYSTEMS AND SHIP DESIGN

by

Jeffrey Lineberry

December 2012

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This thesis addresses the cost estimation portion of the various models and simulations associated with the NICOP initiative, with a focus on Offshore Patrol Vessels (OPVs). This thesis identifies the historical and current ship production costs of OPVs that are used for various combat missions. This study supports the NICOP initiative by providing a foundation for further investigation into the framework necessary to provide more accurate cost estimates. This is accomplished within the trade space of the naval architecture developed through the application of Model Based System Engineering (MBSE). The development of a cost model for the NICOP initiative is used as a framework to explain the cost estimating approach process for future MBSE designs. The model is then used to compare to the base model developed by the Italians.

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ESTIMATING PRODUCTION COST WHILE LINKING COMBAT SYSTEMS AND SHIP DESIGN

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ABSTRACT

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This thesis addresses the cost estimation portion of the various models and simulations associated with the NICOP initiative, with a focus on Offshore Patrol Vessels (OPVs). This thesis identifies the historical and current ship production costs of OPVs that are used for various combat missions. This study supports the NICOP initiative by providing a foundation for further investigation into the framework necessary to provide more accurate cost estimates. This is accomplished within the trade space of the naval architecture developed through the application of Model Based System Engineering (MBSE). The development of a cost model for the NICOP initiative is used as a framework to explain the cost estimating approach process for future MBSE designs. The model is then used to compare to the base model developed by the Italians.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANOVA	Analysis of Variance
AO	Area of Operations
ASNET	Application System for Naval Evaluation and Testing
ASuW	Anti-Surface Warfare
CI	Confidence Interval
DOE	Design of Experiments
INCOSE	International Council on Systems Engineering
JIC	Joint Inflation Calculator
MBSE	Model Based System Engineering
MIO	Maritime Interdiction Operations
MOE	Measure of Effectiveness
NAVSEA	Naval Sea Systems Command
NCCA	Naval Center for Cost Analysis
NICOP	Naval International Cooperative Opportunities in Science & Technology Program
NPS	Naval Postgraduate School
OMOE	Overall Measure of Effectiveness
ONR	Office of Naval Research
OPV	Offshore Patrol Vessel
PRONTO	Partnership for Research on Naval Technology and Operations
SAR	Search and Rescue
SEA 05C	Cost Engineering and Industrial Analysis Division
SEED	Simulation Experiments & Efficient Design

SWBSE	Ship Work Breakdown Structure Elements
USCG	United States Coast Guard
VTOL	Vertical Takeoff and Landing
VUAV	VTOL Unmanned Aerial Vehicle
WHEC	High Endurance Cutter
WMEC	Medium Endurance Cutter

EXECUTIVE SUMMARY

Historically, the shipbuilding process begins with preliminary planning, followed by the creation of the ship platform design, with only minimal consideration for combat effectiveness. This thesis addresses the ability to develop a cost model that estimates ship production costs as combat effectiveness factors are adjusted in the design trade space through the application of Model Based System Engineering (MBSE). We build a cost estimating model that responds in real time to changes in combat systems configurations, namely ship aviation capabilities (e.g., with or without an on-board helicopter), armament configurations (e.g., with or without a 35mm gun system), and maximum speed capabilities.

The Naval Postgraduate School (NPS) Simulation Experiments & Efficient Design (SEED) Center for Data Farming, in collaboration with Office of Naval Research (ONR), is supporting the application of an MBSE approach to naval ship design. The emphasis is placed on advancing the design process within the constructs of the MBSE design. This thesis focuses on the cost estimation process and how a cost estimate should be constructed for MBSE projects. The recursive use of a cost estimating process contributes to the future approach of producing such estimates within the MBSE paradigm.

For this investigation, we built a cost estimating tool that has the ability to produce a ship production cost estimate that is dependent on the combat system configurations. This cost estimating tool allows for further insight on how to develop this tool for other systems. With a deeper investigation on the make-up of this cost estimating tool, we are able to investigate the trade space within the MBSE paradigm. This is accomplished by a focus on the correlation amongst the combat systems and the ship's naval architecture.

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I. INTRODUCTION

A. OVERVIEW

The complete design of a naval combatant ship is an extraordinarily complex process. It can take decades for a design to mature from infancy to delivery of the first ship. Among many problems with this lag is that over 20 years, the requirements that generated the initial design may be long irrelevant, yet a program may be too "invested" to simply abandon it. Additionally, over this period of time, cost estimates which had been deemed "affordable" can evolve into "unaffordable" estimates. Cost estimates must include not only those aspects related to the ship itself, but life cycle costs and any other aspects related to total ownership costs. These costs must be estimated by many points through the design life of the program, in order to determine the best cost versus mission effectiveness trade-offs.

A team of Naval Postgraduate School (NPS) faculty and students, in collaboration with other researchers is utilizing Model Based System Engineering (MBSE) in an approach to develop and demonstrate a methodology to use the output analyses of the combat systems effectiveness as ship characteristic inputs for the ship design process. The specific ship being analyzed and designed in this project sponsored by the Office of Naval Research (ONR) is an Offshore Patrol Vessel (OPV), which serves as an important naval platform for numerous navies. An important aspect of this broad research is to examine impacts of combat system technology trade-offs, and include consideration of cost, risk, and system effectiveness in multiple criteria trade space analysis. Thorough trade space analysis will result from the linkage of combat system capabilities, ship design and selection, and cost estimation, through modeling and simulation.

This thesis focuses on the cost estimation aspect of this problem. In this chapter we provide an introduction of the Naval International Cooperative Opportunities in Science & Technology Program (NICOP) initiative with some clarification to the concept of the MBSE design. Current progress is described in relation to the NICOP initiative for the Partnership for Research on Naval Technology and Operations

(PRONTO)/Application System for Naval Evaluation and Testing (ASNET) project. Focus and clarification for this thesis effort is introduced along with a cost estimating methodology overview.

B. COST ESTIMATING METHODOLOGY

The four common methodologies for producing a cost estimate are Analogy, Expert Judgment, Bottom-Up, and Parametric Models (D. Nussbaum, personal communication, January 2012). Generally, the Parametric and Analogy methodologies are preferred during the earlier design phases and planning of the project, since they can be used in a limited data environment. As the project design matures, additional data will become available, at which point the Bottom-Up methodology can also be employed. Once production is initiated, the use of actual costs to estimate future production costs becomes feasible (D. Nussbaum, personal communication, February 2012). Expert Judgment, although only as strong as the credibility of the expert and lacking any statistical measures of goodness, can be applied throughout the system’s life cycle. Figure 1 shows an association of the preferred estimating methodologies based on the design maturity. As this thesis addresses the early conceptual design phase of an OPV, Parametric and Analogy are the cost estimating methodologies of choice.

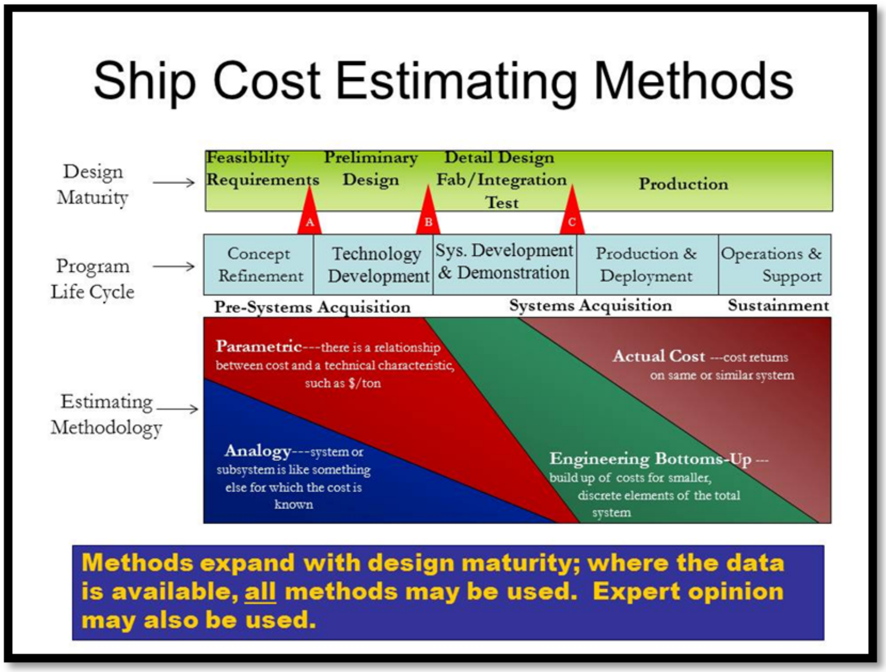

Figure 1. Ship Cost Estimation Methods based on Design Maturity and Program Life Cycle (D. Nussbaum, OA4702, January 2012, from Naval Sea Systems Command Cost Engineering and Industrial Analysis Division, 2008).

This thesis builds a cost estimating model that is responsive to real time changes in combat system configurations. This is accomplished by collecting analogous data and using this data to:

Estimate naval architectural factors (e.g., length, beam, displacement and crew complement) from combat system configurations (e.g., length as a function of crew complement and max speed). These relationships are developed in Chapter IV, which is derivable from full load displacement, as described in Chapter III.

Develop a dollar per pound metric. Since this metric is based on a 4-ship class of United States Coast Guard (USCG) Medium Endurance Cutter (WMEC), we used a learning curve to extend this to an n-ship class.

Applying the dollar per pound metric to the light ship weight described in Chapter III.

C. RESEARCH QUESTIONS

- Develop a cost model that estimates OPV life cycle costs as a function of the design factors within the MBSE design trade space.
- Explain the concepts and development of the life cycle cost model with the purpose of proposing a framework for future cost estimation efforts for the MBSE paradigm.

D. CHAPTER SUMMARY

Chapter I provides an introduction of the concept of the MBSE design paradigm and a cost estimating methodology overview utilized for the efforts pertaining to this thesis' focus. Chapter II provides a deeper insight into the MBSE design concept and cost estimating pertaining to ship designs and system performance, as well as a description of how OPVs are being used in naval operations. Chapter III provides a detailed methodology pertaining to the cost estimating efforts established for the focus of this thesis. Chapter IV provides a detailed description of the production cost estimating dashboard developed for this thesis effort, the analysis done to build the production cost dashboard, and more insight into the use of the dashboard through examples of the dashboard being utilized to reflect early analysis output from the three simulation models being developed at NPS. Chapter V provides a summary and conclusion.

II. PROJECT BACKGROUND AND LITERATURE REVIEW

A. APPLYING MBSE TO DECISION MAKING

1. Introduction to MBSE

The International Council on System Engineering (INCOSE) defines MBSE as "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases"(International Council on System Engineering, 2007). The major distinction of MBSE is that it emphasizes the models as a foundation for the engineering process, represented as a model-focused approach to system designs vice the traditional hardcopy design approach. This form of modeling is possible through the use of computing power (Kleijnen, Sanchez, Lucas & Cioppa, 2005). The ability to simulate the operations and conditions of the system being engineered is a possibility which allows for the MBSE method to test a system before the development phase has begun.

The origin of SE can be traced to Wayne Wymore's mathematical contributions and promotional efforts that led to the recognition of SE as a science (The University of Arizona, 2004). Wymore's book entitled, *Model-Based Systems Engineering: An Introduction to the Mathematical Theory of Discrete Systems* provides an early basis for the conceptualization of SE driven by a model-based framework (Estefan, 2008). MBSE has evolved over the past fifteen years, contributing to accuracy in engineering development and a greater reliance on a wide spectrum of methodologies, processes, and tools (Tepper, 2010). MBSE identifies the driving force of the system, through the effort of models, to analyze and communicate the properties of the system to the engineer. Although there have been many successfully validated projects completed through the use of MBSE, e.g., NASA space suit design, there have also been failures (Cadova, Kovich, & Sargusingh, 2012).

2. Applying MBSE in Trade Space Analysis

This thesis supports an overall NPS effort to improve ship architecture through an understanding of the needed operational effectiveness. The ship platform that serves as the focus for the wide range of our analysis is the OPV. Many navies use OPVs for more than one mission, so the effectiveness of design constructs against the ability to perform several of these missions is addressed. The OPVs in this project are classified by their missions; namely Maritime Interdiction Operations (MIO), Search and Rescue (SAR) and Anti-Surface Warfare (ASuW). When decision makers have the responsibility to select a design, they often do not have the engineering subject matter expertise in order to make an educated and well-informed selection. Simulation and modeling done in the design phase can help to understand how mission effectiveness depends on various engineering factors. These Measures of Effectiveness (MOEs) can be aggregated to represent a single Overall Measure of Effectiveness (OMOE) to decide which ship designs allow the ship to perform as required.

Ensuring the model is able to easily communicate to the decision makers, the creation of a user-friendly computer generated program that involves user interaction, often termed as a 'dashboard', may be utilized. The dashboard should illuminate the trade space and can further simplify the decision maker's duties, giving them a gauge to pose their decision upon by facilitating analysis. The MOEs are critical since they will be the driving force for the decision maker's choices. The utilization of polynomial meta-model functions acting as simulation model surrogates allows exploration within the MBSE design trade space (A. MacCalman, personal communication, May 10, 2012). Linking the operational environment to the simulation models allows for the development of critical MOEs that determine the operational space. On the other side of the spectrum are the naval architectural design parameters that make up the physical space. Both are conducive of the operational requirements that pertain to both ship development and combat effectiveness.

Figure 2 depicts a dynamic process of the MBSE design concept for this project. The left side of the figure describes the factors and requirements that are made up of real-world combat attributes; such as performance and mission effectiveness. At the very top of Figure 2 are the environmental and operational factors which are commonly represented as 'noise' in simulation models. In the center of Figure 2 are the operational requirements pertaining to the mission effectiveness. These operational requirements become the inputs to the simulation models, which are developed to determine the importance of various operational requirement combinations among defined environmental and operational factors.

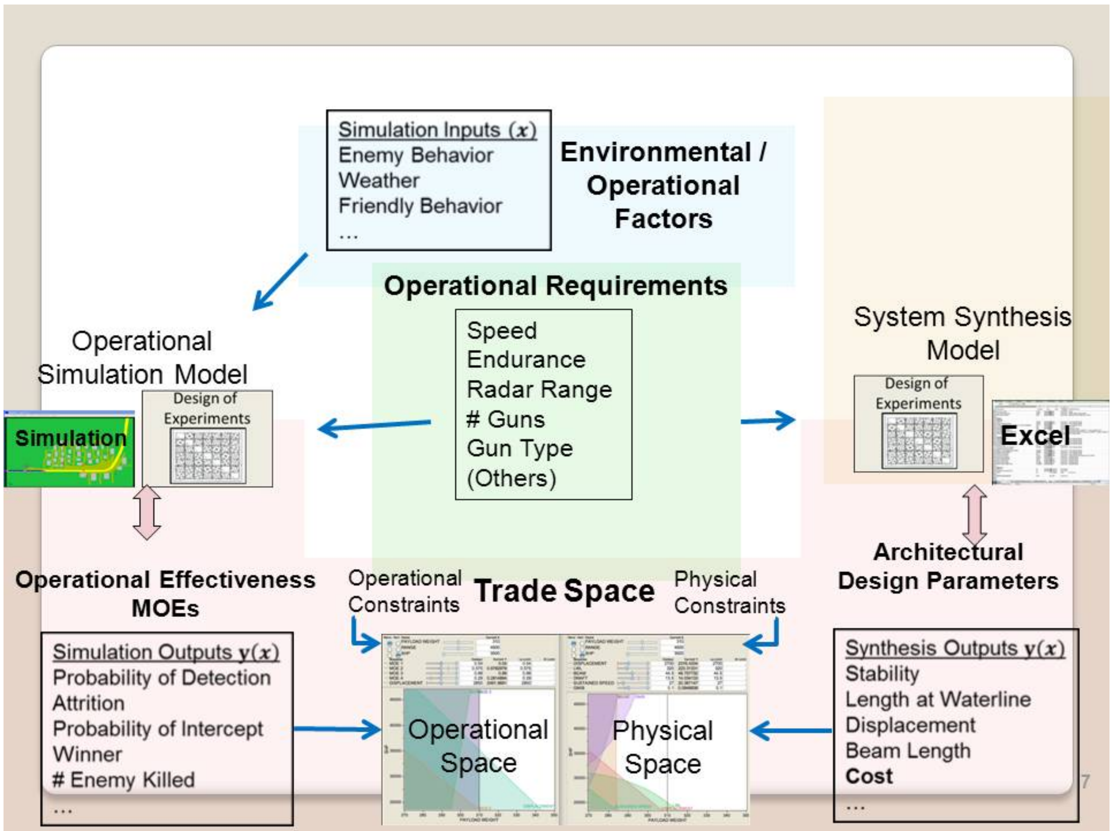

Figure 2. MBSE Design for PRONTO/ASNET Project (From A. MacCalman & E. Paulo, unpublished slide, November 2011)

The simulation outputs are used to determine MOEs. These MOEs, along with existing operational constraints, formulate the operational space of the trade space, which is represented in the bottom center of Figure 2. On the right side of Figure 2, starting at the center, the same operational requirements contribute to system synthesis models that define the architectural design parameters. With the consideration of known physical constraints, theses architectural design parameters mold the physical space. Through the utilization of computing power and scientific design, linking the combat system capabilities and ship design is accomplished by developing an OMOE that defines operational performance. The operational performance is linked to architectural design parameters to reveal acceptable boundaries within the various factors that make up the architecture of the ship. To simplify this concept, the development of a dashboard is used to represent the OMOE and associated architectural considerations.

B. CURRENT PROJECT PROGRESS

NPS's contribution to the project is incorporating naval operational insights into the simulations analysis, to include a focus on cost estimation. Three simulation models are being built to add more insight into the naval tasks they represent, and additional work is being done to develop a dashboard, which serves as a dynamic decision tool.

Royal Thai Navy CDR Yoosiri Peerapong has developed a MIO simulation utilizing MANA, which defines the mission more accurately. His main objectives were identifying significant parameters affecting the MIO mission along with the additional analysis of the improvement capabilities of a Vertical Takeoff and Landing (VTOL) Unmanned Aerial Vehicle (VUAV) (Yoosiri, 2012).

LT Joseph Ashpari is investigating the SAR mission with the purpose of investigating the importance based on factors of OPV maximum speed, employment of a combination of helicopters and VUAVs on board (Ashpari, 2012)

LT Jason McKeown has developed an ASuW simulation utilizing MANA. An advanced model is being developed in order to more realistically represent real-world implications, such as clarifying kill probabilities of armament aboard the ship, various sizes and amount of armament, programming the small attack boats to have intelligent deterrence capabilities, the ability to increase the number of small boat attackers and the development of a more realistic noise component by including friendly and neutral boats in the operating area (McKeown, 2012).

Mr. Paul Beery and Mr. Paul Roeder have collaborated on the development of a dashboard that allows exploration of the operational and synthesis meta-models, involving value modeling that assesses the three operational scenarios in relation to each other. This dashboard is visually represented by an ability to move crosshairs within either space to explore the synthesis meta-model that illustrates both the operational and physical aspects of the trade space as depicted in Figure 3. This dashboard has integrated the cost estimating parametric equations, representative of this thesis effort (P. Beery & P. Roeder, unpublished dashboard, 2012).

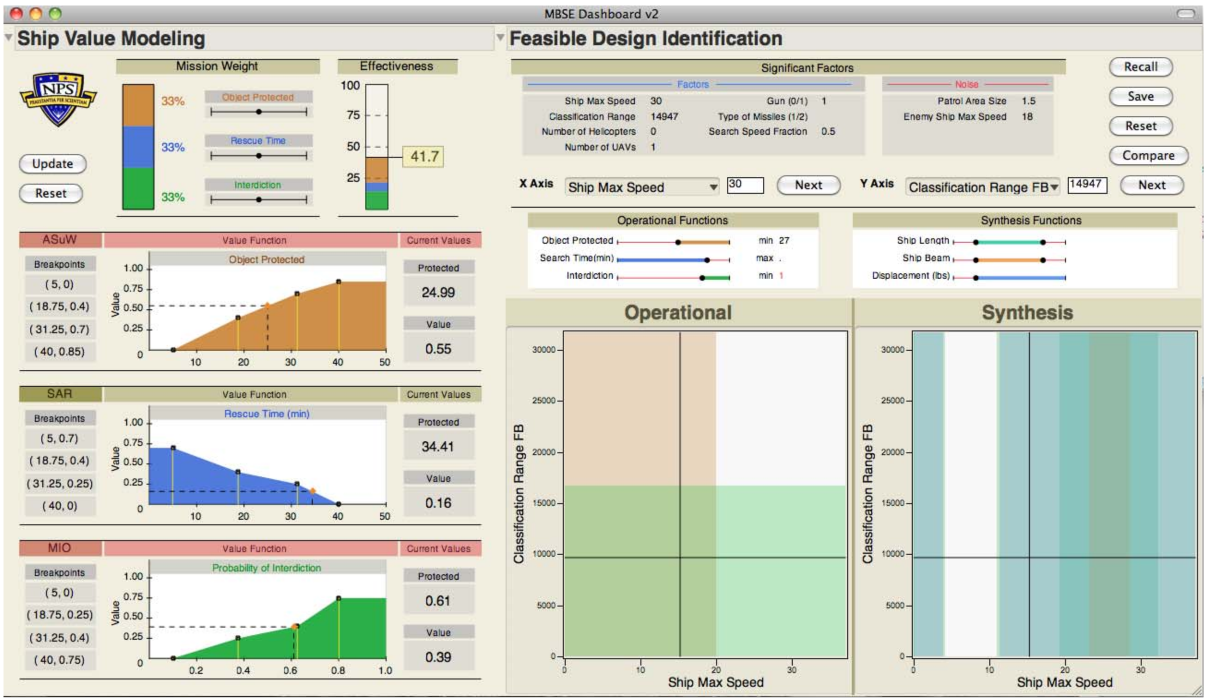

Figure 3. NPS Dashboard for PRONTO/ASNET Project (P. Beery & P. Roeder, unpublished dashboard, June 7, 2012).

C. COST ESTIMATING NAVAL SHIP DESIGNS

1. Estimating Construction Costs in the Design Phase

Understanding how the design affects costs is crucial to any project. With the onset of new technologies and increasing labor and material costs, costs overruns are still a common phenomenon (Arena, 2006). The more complex a ship is, the more difficult it is to trace the design costs of the ship. This is an important factor for knowing where to budget investment without affecting other attributes in the construction process. The ability to manage cost information is crucial, although it does not give the ability to identify an accurate budget proposal before the production phase of the development life cycle (Fischer & Holbach, 2011). The early stages of ship design are very complex, where many decisions must be made with a minimal amount of knowledge and a great amount of risk, especially when new concepts are introduced (Hockberger, 1996). Producing a cost estimate during this early design stage has important consequences since this is where a ship construction budget will be imposed, and the decision of where to allocate money will be implemented.

2. Estimating Costs as a Function of Performance Levels

Estimating costs for levels of performance during the design phase is rarely done. Rather, naval architectural design parameters are the usual cost drivers, so that the ability to identify the critical attributes affecting the system and its interactive flow is a proposed step towards this idea of costing performance (Brown & Salcedo, 2003). Linking effectiveness to design is the concept encapsulated in the MBSE paradigm (Piaszczyk, 2011).

III. DETAILED METHODOLOGY

In this chapter we describe the data obtained for the cost estimating effort and the data analysis methodology. Historically, ship weight and ship costs are positively correlated, and regression analyses have been used to model their relationship. In particular, light ship weight is a good predictor of costing "simple" ships which have historical antecedents (Miroyannis, 2006). By "simple", Miroyannis means single-hull ships such as OPVs, and we apply this weight based approach to estimating the costs of OPVs.

A. COLLECTING AND ORGANIZING THE DATA

Data on OPVs were obtained from Jane's Fighting Ships, Dr. Dan Nussbaum and Naval Sea Systems Command (NAVSEA) Cost Engineering and Industrial Analysis Division (SEA 05C). We describe these datasets below.

1. Jane's Fighting Ships

We collected data on 45 OPVs from 28 nations. These data points are in Table 1.

Table 1. Compiled Ship Data from Jane's Fighting Ships (After Jane's Fighting Ships, 2012).

Nation	Ship Class	Displacement (lbs) full load	Length (ft) overall	Beam (ft) overall	Max Speed (kts)	Crew	Helicopter
Russian Federation	Komandor class	5442200	289.7	44.62	20	42	2
US & Philippine	Cyclone class	848800	179	25	35	29	0
US	National Security Cutter	9211000	418	54	28	148	2
US	WMEC Famous class cutter	4012400	270	38	19.5	113	1
US	Hamilton Class	7392000	378	43	29	162	1
US	WMEC Reliance class cutter	2248800	210	34	18	75	1
Brazil	OPV (PSO)	5039800	296.9	44.3	25	94	1
Thailand	Krabi	5599800	296.9	44.3	25	50	1
Argentina	OPV (PSO)	4144600	262.5	42.7	21	60	1

Nation	Ship Class	Displacement (lbs) full load	Length (ft) overall	Beam (ft) overall	Max Speed (kts)	Crew	Helicopter
Montenegro	Kotor class	4188800	317	42	27	110	1
Taiwan	PSO	4640800	323	43	24	68	1
Turkey	Dost class	3807400	291	40	22	65	1
Spain	Meteoro class	6261200	308	47	20.5	50	1
Colombia	PSO	3798600	264	43	20	40	1
India, Mauritius	Vikram class	2866000	243	37	22	84	1
India	Vikram class	2742600	243	37	22	107	1
Venezuela	Guaiqueri class	5227200	324.46	44.62	24	60	1
United Kingdom	River Class	3807400	261.65	44.62	20	66	1
United kingdom	Modified River Class	4138000	267.9	44.62	20	77	1
Spain	Alboran class	4398200	218.18	36.09	13	53	1
Portugal	Viana Do Castelo	4118200	272.64	42.29	20	43	1
Malta	Diciotti class	879600	175.2	26.57	23	29	1
Spain	Serviola class	2568400	225	34	19	56	1
Malaysia	Langkawi class	2912400	246.06	35.43	22	86	1
Turkey	Milgem class	4479800	325	47	29	106	1
France	Gowind corvette	3307000	285.43	42.65	21	59	1
France	Florȇal class	6607200	306.76	45.93	20	131	1
Italy	Cassiopea class	3304800	261.81	38.71	20	70	1
US	Asheville	527000	164.37	23.95	35	28	0
US	Sentinel	791400	153.22	25.26	28	22	0
US	Island	377000	109.91	21	29	18	0
Latvia	Valpas	1221400	159.1	27.9	15	18	0
Iraq	OPV (PSO)	3086400	197	37	16	42	0
Finland	Improved Tursas class	2464800	190	36	15	30	0
Finland	Tursas class	2799800	202	33	14	32	0
Taiwan	PBO	4085200	277	41	20	40	0
Lebanon	PSO	584200	143	27.9	25	6	0
India	Rani Abbakka class	615000	168	27.6	34	35	0
Venezuela	Constitución class	381400	121	23.3	31	24	0
Trinidad, Tobago	PBO	447600	151.9	29.86	20	19	0
Sri Lanka	Jayesagara Class	738600	130.58	22.97	15	56	0
Taiwan	WPBO	1878400	168.96	27.56	16	22	0
Taiwan	WPSO	2522000	193.24	31.5	16	25	0
Taiwan	WPSO	1567400	201.44	31.17	30	33	0

Nation	Ship Class	Displacement (lbs) full load	Length (ft) overall	Beam (ft) overall	Max Speed (kts)	Crew	Helicopter
Spain	Pescalonso class	4706800	222.44	36.09	12	42	0

2. NAVSEA 05C Production Cost Data on USCG's 270' WMEC

NAVSEA 05C provided cost data for the first four ships in production of the USCGs 270ft WMEC. The data consisted of weight, total man-hours, and total material dollars for each of the Ship Work Breakdown Structure Elements (SWBSE) in Table 2. All data was reported in US FY77$ and we normalized it to US FY12$.

Table 2. SWBSE acquired from NAVSEA data (After NAVSEA 05C).

100—Hull Structure
200—Propulsion Plant
300—Electrical Plant
400—Command and Surveillance
500—Auxiliary Systems
600—Outfit and Furnishings
700—Armament
800—Integration/Engineering
900—Ship Assembly and Support Services

The data obtained of the 270ft WMEC was obtained from NAVSEA 05C who informed us that these data are competition sensitive. Therefore these data are not included in this written thesis. It may be acquired from NPS Operations Research Professor, Dr. Dan Nussbaum, on a case-by-case basis.

3. Dr. Nussbaum's OPV Weight Data

Light ship weight data in short tons (US) was acquired from Dr. Nussbaum for three USCG cutters. These data are described in Table 3.

Table 3. Light ship weight data in lbs. (After Dr. Nussbaum).

WMEC Famous class cutter	2899456
Hamilton Class	5412480
WMEC Reliance class cutter	1710867.2

B. NORMALIZING THE DATA

1. Analyzing Factors

Naval architecture involves many factors, but our focus on a single type of ship, a single hull OPV, permits us to narrow our considerations to four factors: displacement, length, beam, and crew complement.

Displacement is a confusing part of naval architecture because of the many different definitions that involve the word "displacement." In this thesis, we use full load displacement, which is defined in detail in chapter IV. Since we are dealing with a single hull ship, we know we will be relying on the displacement attributed to weight support (Tupper & Muckle, 1996). Since light ship weight can be modeled as a function of full load displacement (see page 40) it is sufficient for our purposes to collect full load displacement data. Full load displacement is reported in datasets such as Jane's Fighting Ships.

Flotation and stability requirements impose hull-development relationships on length and beam, which in turn constrain the architectural volume of a ship, its on-load weight capacity, crew size, and other associated design parameters (Tupper & Muckle, 1996).

Since each piece of equipment has an associated crew complement, attention must be placed on the volume requirements associated with the mission of the ship.

2. Units of Measure and Conversions

We used the following definitions, conversions, and combat system identities for this thesis:

Light ship weight, measured in pounds, is the weight of the ship without payload. That is, light ship weight = displacement (full load) – total deadweight including payload, ballast water, provisions, fuel, lubricants, water, persons, and personal affects (Schneekluth, Knovel, & Bertram, 1998). Full load displacement is light ship weight plus the ship's total deadweight. Maximum speed capabilities are reported in knots (kts). Crew complement is reported in the number of people. Helicopters refer to mid-sized helicopters. We utilized cost data on the Augusta Westland Lynx, as depicted in Figure 4, to estimate the cost of an mid-sized helicopter to be US 31M FY12$ (Jane's All The World's Aircraft, 2011). From the data distribution in Jane's Fighting Ships, we determined the average crew complement for OPV's as a function of the employment of on-board helicopters and armament configuration. Armament configurations investigated consisted of missiles and a 35mm gun system. Missiles used for both the Italian base model and this investigation were Exocet and Marte type, images of which are in Figure 5. The cost of an Exocet missile was determined, by analogy to the Harpoon missile, at US 1.2M FY12$ (U.S. Navy, 2009). The cost and crew complement of a Marte missile were estimated as half those of the Harpoon's. Cost data on an Italian 35mm gun system, depicted in Figure 6, was determined through expert judgment (A. Bonvicini, personal communication, July 30, 2012). VUAVs were determined to be half the size of a helicopter based on operational considerations reported on the USCG National Security Cutter (Beshears & Peterson, 2004). The cost of a VUAV was determined using cost data from the USCG's Eagle Eye VUAV, depicted in Figure 7, with an estimated cost of US 11.2M FY12$

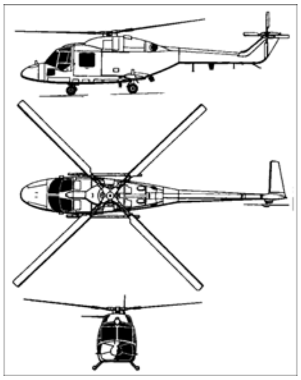

Figure 4. August Westland Lynx (From aviationsmilitaires.net)

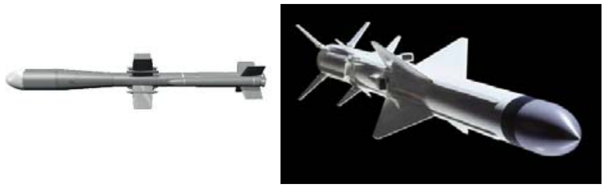

Figure 5. Marte [Left] (From MBDA Missile Systems),Exocet [Right](From Surbrook-Devermore)

Figure 6. Italian Ship 35mm Gun (From navweaps.com).

Figure 7. USCG Eagle Eye VUAV (From Wikipedia).

3. Normalization

All cost data was converted to US FY12$, using the Joint Inflation Calculator (JIC), at the Naval Center for Cost Analysis (NCCA) (Naval Center for Cost Analysis, 2011).

C. REGRESSION METHODOLOGY

Our interactions with PRONTO/ASNET partners reveal differences on the application and interpretation of various analytical methods. In this section we identify our methodology on regression analysis and the software package utilized in our cost estimating efforts.

1. Multicollinearity

Multicollinearity occurs when two or more dependent variables are highly correlated, thus causing an overlap between the marginal contributions of the independent variables. Looking at a pairwise correlation matrix is an advantageous way to identify variables that are highly correlated. In this thesis, two variables are considered to be multicollinear if their correlation coefficient is greater than or equal to 70%. We utilized JMP's Multivariate Analysis tool for our calculation.

2. Measures of Goodness of Fit and Cost Results

The analysis tools for JMP were utilized to investigate distributions and perform regressions for this thesis. In utilizing the "fit model" tool in JMP, a stepwise fit was first investigated with dependent variables inclusive of all response surfaces for model effect construction. The stepwise option allowed us to achieve the best regression fit by facilitating a search and selection operation among many model variations. Further determination of a good fit was confirmed by looking at the Lack of Fit's p-value of the F-statistic, the Parameter Estimate dependent variable's p-value of the t-statistic, and the Summary of Fit's R^2 and R^2 adjusted. Confidence Intervals (CI) for the parameter estimates were also calculated.

a. Prob > |t|

Assist in determining whether the dependent variable is "useful" in the model. If less than alpha then we prefer the dependent variable in our model. In JMP, this is associated with a p-value next to the variables regressed. An asterisk is associated with acceptable p-values for dependent variables in the fit.

b. Prob > F

Informs whether the overall model is preferred to the mean of the original dependent variable values. In JMP the F statistic signifies the differences between groups with respect to their means, the lower the probability that the population means are equal, the more significant the regression model is.

c. R^2 and R^2 adjusted

Indicates that potion of Total Variation is accounted for by the regression. It is also an indicator of our confidence in predicted values. In JMP R^2 is utilized for model comparison with the same number of regressors while R^2 adjusted is utilized for model comparisons with a varying number of regressors. Indication that a model has a better fit is by determining the greatest R^2.

d. CI

Provides a lower and upper estimate which allows an association of risk based on the alpha level, thus indicating the reliability of the estimate. In JMP, you can set the alpha level via model specifications right before fitting your model. This will provide output of the upper and lower parametric equations associated with your desired confidence level.

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IV. COST ANALYSIS

In this chapter, we provide a detailed description of the production cost estimating dashboard along with the "under the hood" analysis that was used to build it.

A. PRODUCTION COST ESTIMATION DASHBOARD

1. Development

A dashboard was created that quickly displays the changing OPV production cost estimate as a function of combat system configuration and mission dependent combat capabilities. This dashboard is one of several parallel efforts being built by NPS students for the PRONTO/ASNET NICOP initiative.

The inputs for the dashboard are: maximum speed capability, number of on-board helicopters, number of on-board VUAVs, number and type of missiles on board (Marte or Exocet), the inclusion of a 35mm gun system, the presence of a helicopter in the Area of Operations (AO), and the number of OPVs to be produced. These inputs are requested through a visual basic pop-up screen when the program is opened. The input screen of the dashboard is depicted in Figure 8.

The output screen of the dashboard can be viewed in Figure 9. It displays the cost estimates (in US FY12$M), and 80% CI, for:

- First OPV in production (so-called "T1")
- Average cost of all OPVs produced, and the distribution of this estimate across the single digit SWBSE.
- External costs of helicopters, VUAVs, the 35mm gun system, and missiles, as well the total of these items
- The learning curve associated with OPV production
- The associated overall length, overall beam, full load displacement, average crew complement, light ship weight, and average dollar per pound, for a ship which is the average of current OPVs in operation.

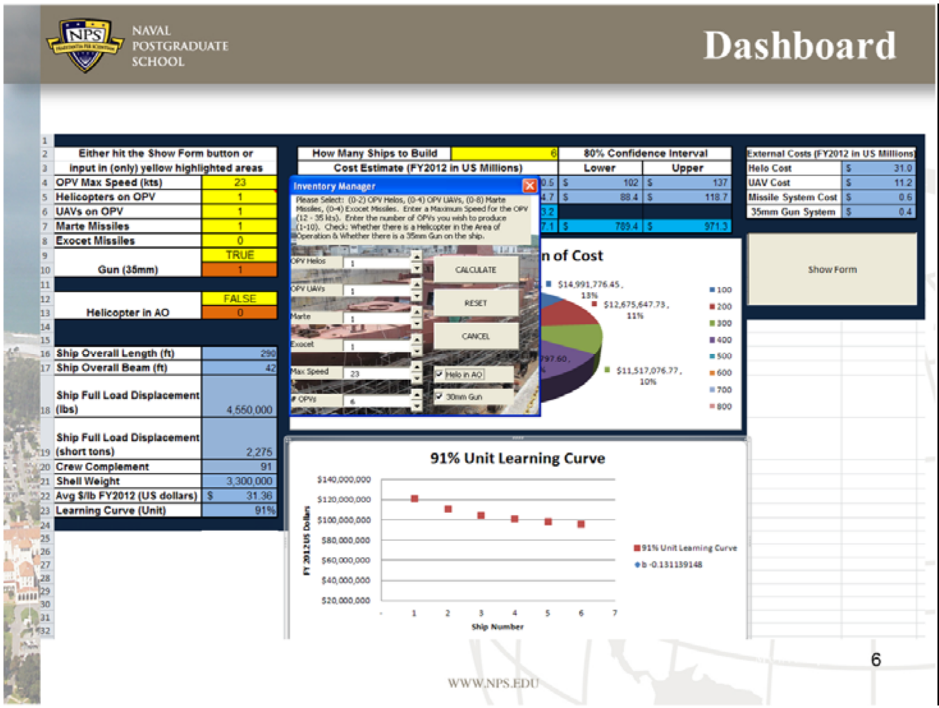


Figure 8. Opening, Input, page of the Dashboard

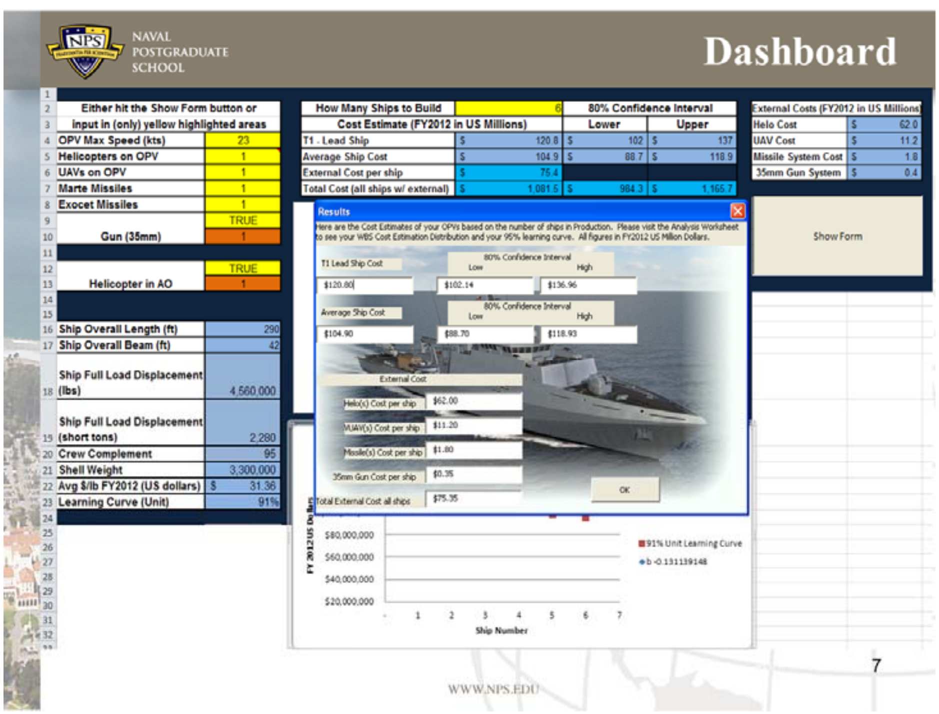


Figure 9. Output page of the Dashboard

The dashboard's purposes are to develop and display production cost estimate, based on various combat configurations. The dashboard user configures the combat components through inputs of: the number of OPV's to be produced, the number of on-board helicopters and on-board VUAVS, the type and amount of missiles, maximum speed capability, whether the OPV will use a 35mm gun system, and whether the use of a helicopter is in the OPV's AO (The dashboard quickly provides an average ship production cost estimate with an 80% CI for this cost estimate. This estimate is developed through a series of steps that produces a flow of information. This flow is determined by:

- Average crew complement, based on aerial assets and weapon configurations.
- Maximum speed, which is an input variable for this model.
- Length, which is determined by a parametric equation built from maximum speed and crew complement via JMP.
- Beam, determined through a parametric equation built from length via JMP.
- Full load displacement, determined through a parametric equation built from beam via JMP.
- The parametric equation from the regression analysis performed on light ship weight against full load displacement via JMP.
- The $34.64 per pound calculation, based on the production of four 270ft WMECs, which was calculated from the NAVSEA 05C data.

Figure 10 displays this flow, called a "Synthesis Flow," along with associated parametric equations and associated R^2 values.

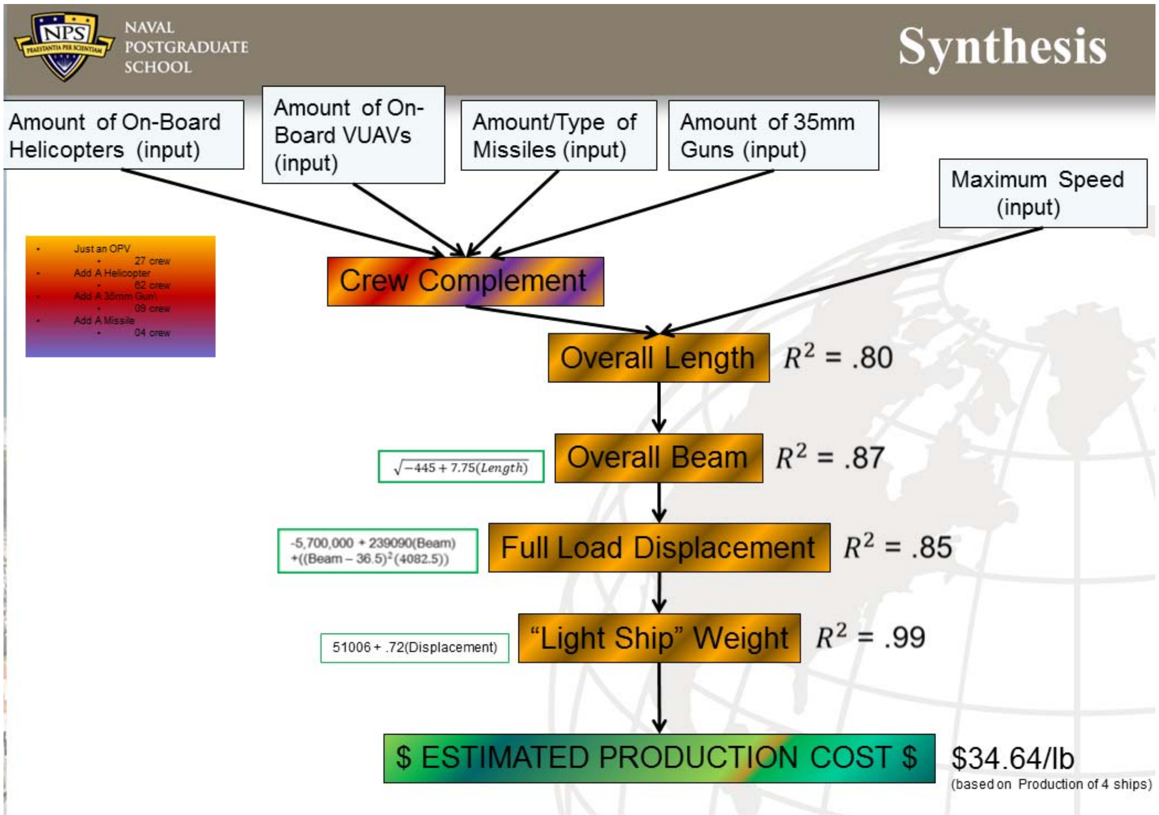


Figure 10. Synthesis Flow via Distributional and Regression Analysis

B. ANALYZING THE DATA

1. Jane's Fighting Ships

Jane's Fighting Ships provided data on 45 OPVs from 28 different nations. This data represented OPVs that ranged between 109 to 418ft in overall length, 21 to 54ft in overall beam, 377,000 to 9,211,000lbs of full load displacement (188.5 to 4,605.5 short tons), 12 to 35kts of maximum speed capabilities, complemented with crews between 6 to 162 sailors, having the capability to hold either 0, 1, or 2 medium sized helicopter(s), and armament configurations consisting of missiles representative of Exocet or Harpoon missiles, or missiles similar in dimension and performance, and guns ranging from 7.62mm to 100mm (Jane's Fight Ships, 2012).

The six figures in Figure 11, provide the distribution of the OPV factors from these 45 data points. For example, looking at the distribution of length we can see that although the ships represented by the data range from 100 to 450ft, the majority of them are between 150 and 300 ft. We can see that this distribution holds a Normal 3 Mixture property, which can indicate normality once the data is separated, as seen in the darker portion of the graph between 150 to 450ft.

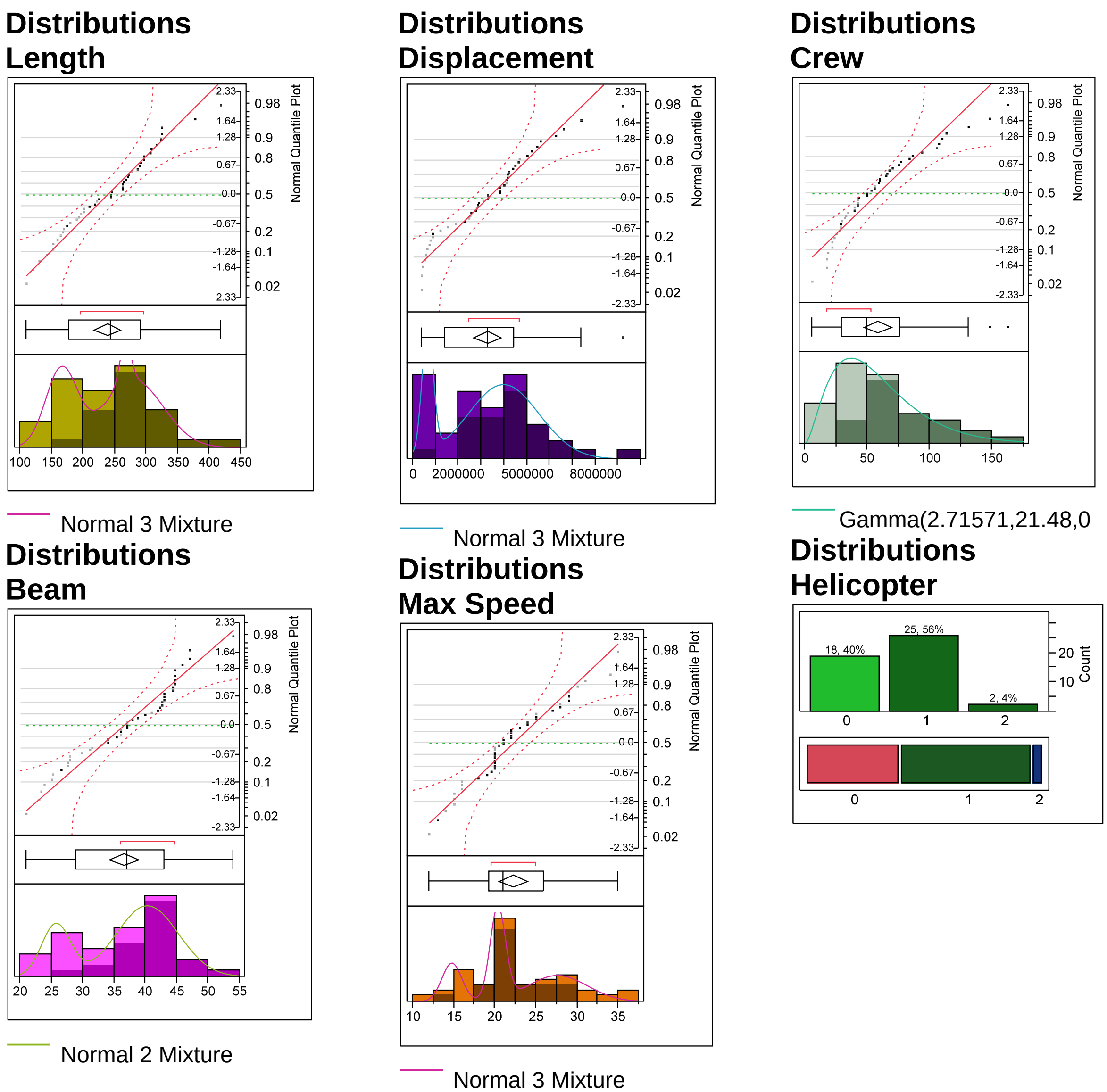
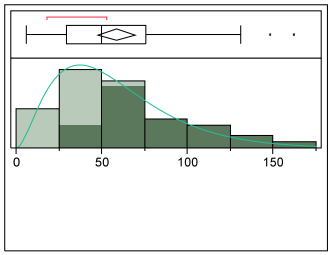


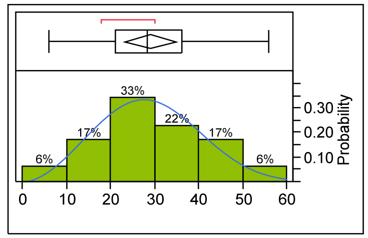
Figure 11. Distributions of OPV Factors

The data was further investigated to determine, on average, how many crew members are necessary to man a ship as a function of the presence of on-board helicopters, VUAVs and armament configurations. Figure 12 displays crew complement distributions investigated by on-board helicopter(s). Figure 13 shows a one way Analysis of Variance (ANOVA) of crew complement for OPVs investigated by the amount of on-board helicopter(s) Investigations into these distributions and ANOVA allowed us to realize that there was a strong association between crew complement and on-board helicopter(s).

Distributions of Crew—all OPVs



Distributions of Crew of OPVs with 0 Helicopters



Distributions of Crew of OPVs with 1 Helicopter

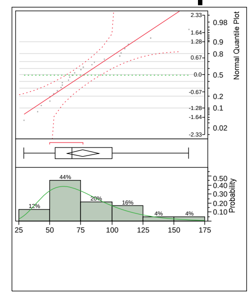


Figure 12. Distribution of Crew Complement based on Number of On-Board Helicopter(s).

One-way ANOVA of Crew by Helicopter

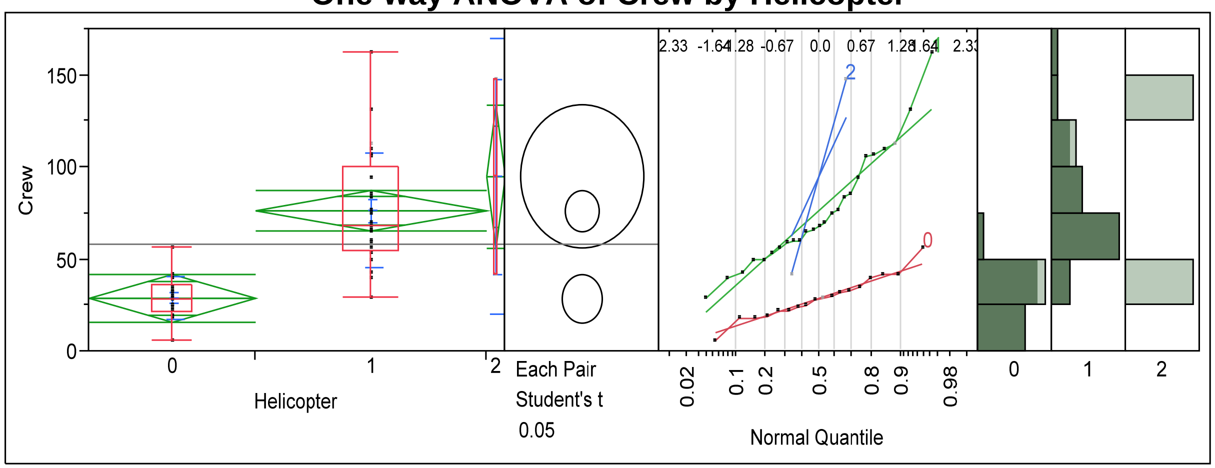


Figure 13. One-way ANOVA of Crew Complement by Number of On-Board Helicopter(s)

2. NAVSEA 05C Production Cost Data on USCG's 270' WMEC

We estimated fully burdened labor cost at $66/hr, built up as follows:

- A mean rate for ship and boat building of $22/hour from the Bureau of labor Statistics (BLS) plus
- A "wrap rate", to cover overhead, general and administrative cost, profit, and fringe benefits, of 200% (Bureau of Labor Statistics, 2011 & D. Nussbaum, personal communication, February 15, 2012).

We then estimated ship production cost on a dollar per pound basis. We used $34.64/lb which we developed by considering both the labor cost and material cost per ship, averaged across the four WMEC ships for which we have data. This dollars-per-pound estimate is further allocated to the nine SWBS elements, in proportion to weight, as shown in Figure 14.

Further, we developed a unit-theory learning curve from the four data points, and we used this learning curve to estimate costs for ships beyond a four-ship class. Figure 15 depicts the learning curve, which has a first unit cost of 111 US FY12$M and a learning curve slope of 91% .

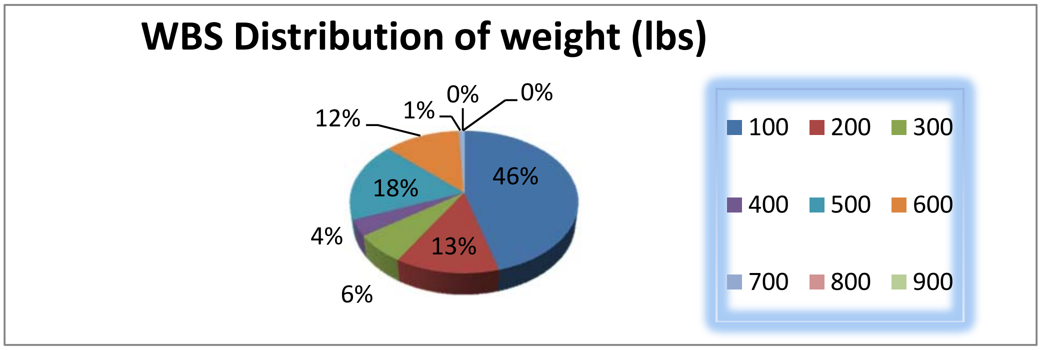


Figure 14. Distribution of Weight (lbs) based on single digit SWBSE (After NAVSEA 05C)

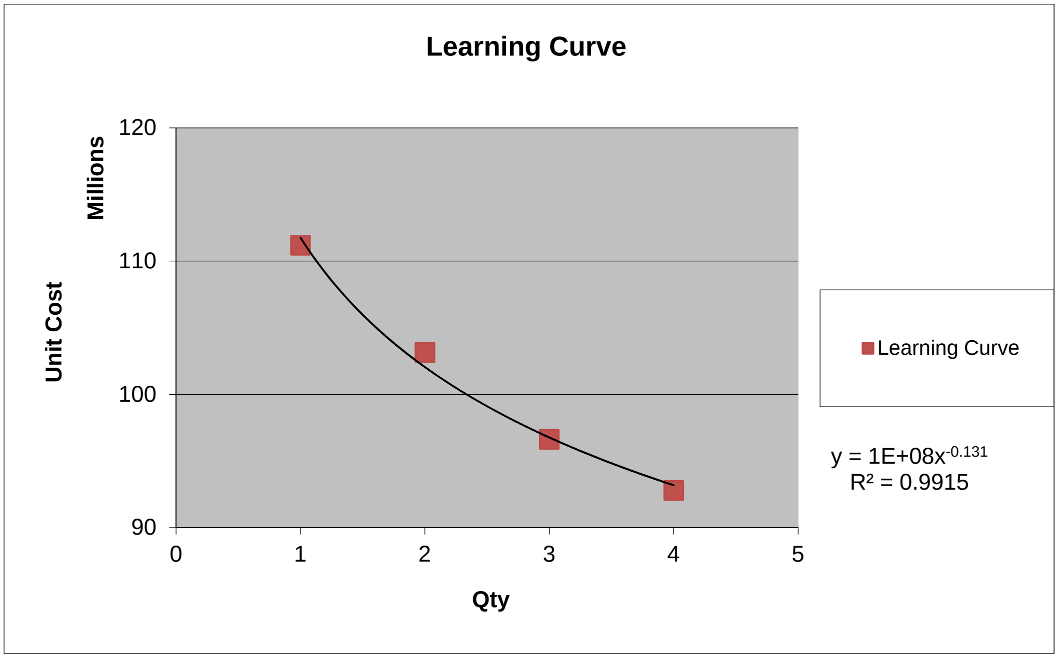


Figure 15. Learning Curve associated with NAVSEA 05C 270 ft WMEC Data (After NAVSEA 05C)

3. Dr. Nussbaum's OPV Weight Data

Light ship weight data was acquired for three USCG cutters: The 378ft High Endurance Cutter (WHEC) at 5,412,480lbs, the 270ft WMEC at 2,899,456lbs, and the 210ft WMEC at 1,710,867lbs. We used these three data points to model light ship weight as a function of full load displacement. The three data points are listed in Table 4, where deadweight is calculated by subtracting light ship weight from full load displacement.

Table 4. Light Ship Weight Data displayed in JMP Database.

	Nation	Ship Class	Light Ship Weight	Displacement full load (lbs)	Deadweight (lbs)	Length (ft) overall	Beam (ft) overall	Max Speed (kts)	Crew Complement	Helicopter	Gun 76mm	Gun 25mm
1	US	WMEC Famous class cutter	2899456	4012400	1112944	270	38	19.5	113	1	1	0
2	US	Hamilton Class	5412480	7392000	1979520	378	43	29	162	1	1	2
3	US	WMEC Reliance class cutter	1710867.2	2248800	537932.8	210	34	18	75	1	0	1

C. DISTRIBUTION ANALYSIS

Crew complement was determined for each of four OPV configuration. For each configuration, we used the mean crew complement of similarly configured OPVs in Jane's Fighting Ship. Descriptive data are displayed in Figure 16 and Table 5 displays means for each configuration The four configurations are:.

- An OPV without an on-board helicopter and without a gun system or having guns smaller than 30mm
- An OPV without an on-board helicopter with a 30mm gun system or greater
- An OPV with an on-board helicopter and gun system less than 25mm
- An OPV with an on-board helicopter and a gun system between 25mm and 35mm.

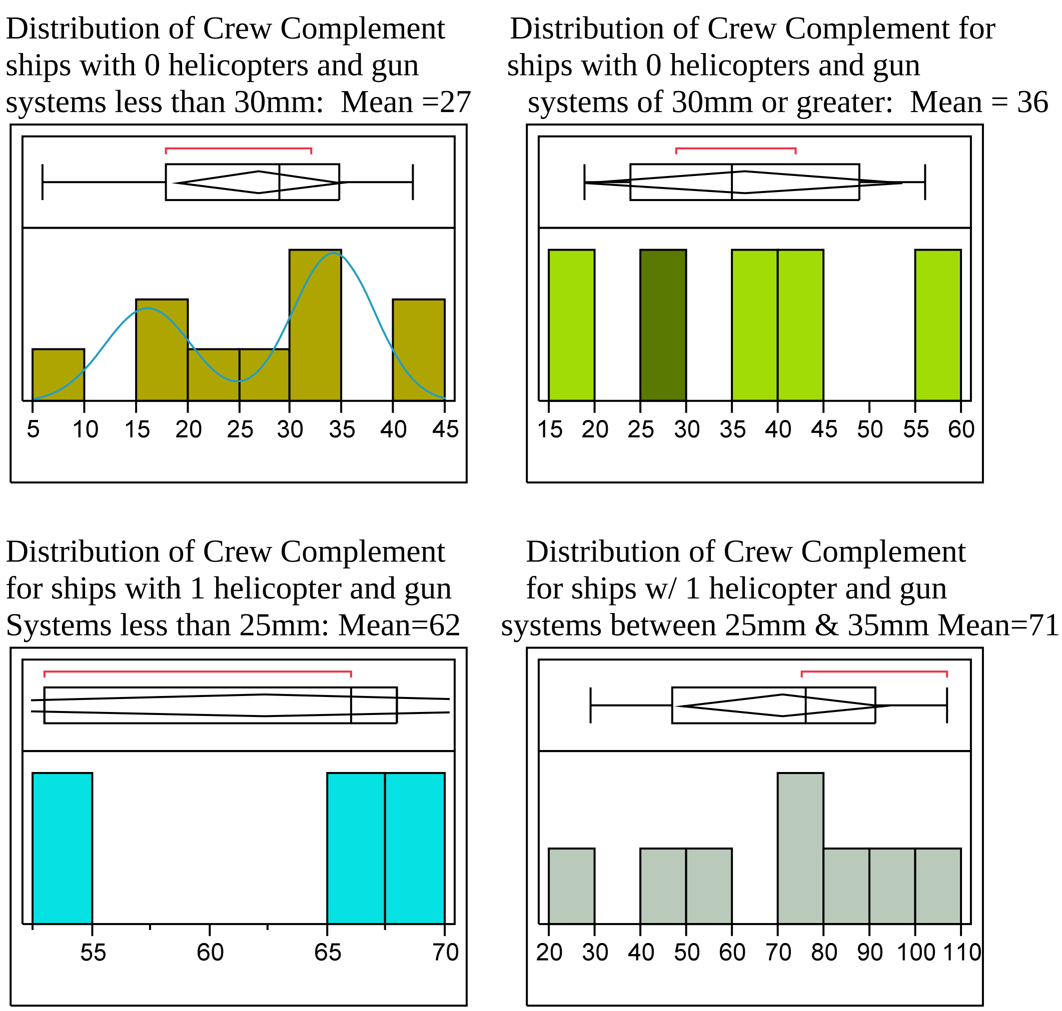


Figure 16. More Detailed Distribution Analysis of Crew Complement

Table 5. Average Crew Complement based on 35mm Gun System and 1 On-Board Helicopter.

OPV configuration	Mean Crew Complement	Notes
no on-board helicopter no 30mm gun system	27	Just a ship would require, on average, 27 sailors
no on-board helicopter with a 30mm gun system	36	Adding a gun system would require, on average, 9 additional sailors
1 on-board helicopter no 30mm gun system	62	Adding a helicopter would require, on average, 35 additonal sailors
1 on-board helicopter with a 30mm gun system	71	Adding a helicopter and a 35mm gun system would require, on average, 44(35 + 9) additional sailors

We are still estimating crew size, this time only for combat factors not mentioned in the distributional analysis. An OPV with two on-board helicopters was determined by taking the average of the only two reported OPVs employing two helicopters from the Jane's Fighting Ships data, resulting with an average crew complement of 95 people. VUAV's were determined by the fact that they were reported to take up nearly half the operating space via the insight gained on a report of the USCGs National Security Cutter. Therefore the average crew complement was calculated in associated progression steps, based upon the on-board helicopter(s) average crew complement. Missiles were determined from the data of four ships from the Jane's Fighting Ships data. By removing the determined crew complements and performing calculations based upon each missile, a crew complement average was determined to represent each missile with four persons. The missiles reported in the data were either Exocet or Harpoon, which are both very similar in size and payload. A crew complement for Marte missiles were determined by halving the average crew complement estimated for Exocet type missiles, setting average crew complement down to two persons per Marte missile.

D. REGRESSION ANALYSIS

We used JMP to investigate multicollinearity and to do stepwise regression.

1. Multicollinearity

We checked the data from Jane's Fighting Ships for multicollinearity, and we found significant linear relationships among displacement, length and beam, as highlighted in the pairwise correlation matrix provided in Table 6 and graphically depicted in Figures 17 and 18.

Table 6. Multivariate Correlations of OPV factors.

MultivariateCorrelations

	Displacement	Length	Beam	Max Speed	Crew
Displacement	1.0000	0.9285	0.9134	-0.1349	0.7155
Length	0.9285	1.0000	0.9355	0.0425	0.7737
Beam	0.9134	0.9355	1.0000	-0.1449	0.6509
Max Speed	-0.1349	0.0425	-0.1449	1.0000	0.1028
Crew	0.7155	0.7737	0.6509	0.1028	1.0000

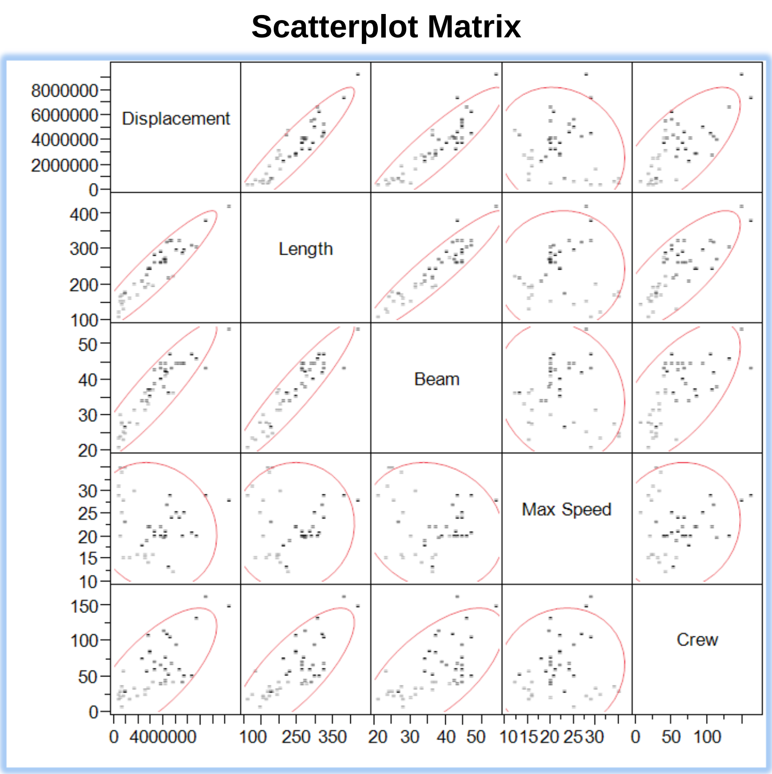


Figure 17. Graphical Representation of the Correlation between OPV factors.

Ellipsoid 3D

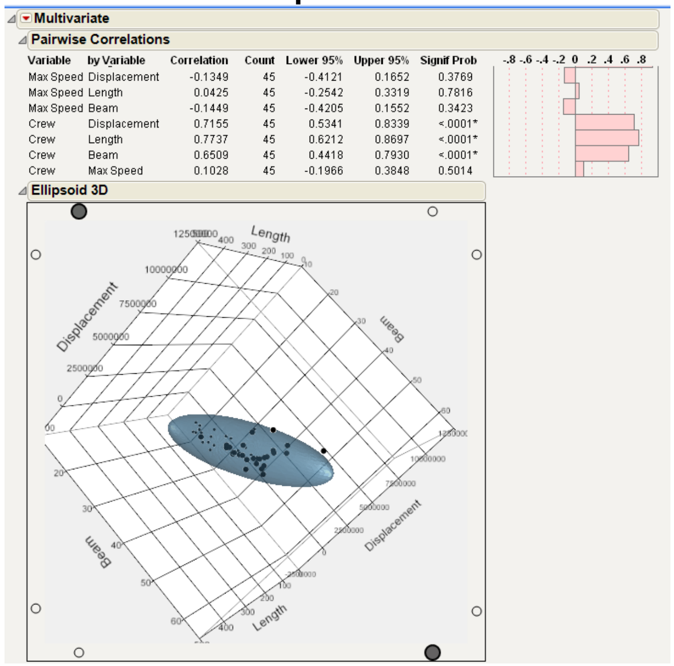


Figure 18. 3D Plot Showing Strong Multicollinearity between OPV Factors: Length, Beam and Displacement

2. Overall Length

We modeled length, using a stepwise fit, against crew complement and speed. The output to the regression analysis is in Table 7, with the highlighted items confirming significance in the model and the model parameters. Further interactions between overall length against crew complement and maximum speed capability allows for further investigation on how length is determined. In Figure 20, you can see that length has a saddle-point in its graphical representation of the factors interacting with crew complement and maximum speed. This observation allows us to recognize that adding on-board helicopter may add to cost.

Table 7. JMP Regression Output for Overall Length.

Summary of Fit

RSquare	0.802056
RSquare Adj	0.770801
Root Mean Square Error	16718.72
Mean of Response	61482.21
Observations (or Sum Wgts)	45

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	4.3038e+10	7.173e+9	25.6622
Error	38	1.0622e+10	279515651	**Prob > F**
C. Total	44	5.366e+10		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	5869.5891	15085.64	0.39	0.6994	-24669.69	36408.873
Max Speed	2165.3316	602.9703	3.59	0.0009*	944.68194	3385.9812
Crew	387.05542	133.3916	2.90	0.0061*	117.01816	657.09267
(Max Speed-22.2222)*(Max Speed-22.2222)	-221.7492	71.91482	-3.08	0.0038*	-367.3331	-76.16524
(Max Speed-22.2222)*(Crew-58.3333)	62.442609	19.13465	3.26	0.0023*	23.706538	101.17868
(Crew-58.3333)*(Crew-58.3333)	-11.41778	3.231594	-3.53	0.0011*	-17.9598	-4.875764
(Crew-58.3333)*(Crew-58.3333)*(Crew-58.3333)	0.115227	0.042296	2.72	0.0097*	0.0296035	0.2008505

Prediction Expression

$$\sqrt{\begin{aligned}&5869.58906491833\\&+2165.33158722265*\text{Max Speed}\\&+387.055415000061*\text{Crew}\\&+\left(\text{Max Speed}-22.2222222222222\right)*\left(\left(\text{Max Speed}-22.2222222222222\right)*-221.74917920014\right)\\&+\left(\text{Max Speed}-22.2222222222222\right)*\left(\left(\text{Crew}-58.3333333333333\right)*62.4426094720016\right)\\&+\left(\text{Crew}-58.3333333333333\right)*\left(\left(\text{Crew}-58.3333333333333\right)*-11.4177\right.\\&+\left(\text{Crew}-58.3333333333333\right)*\left(\left(\text{Crew}-58.3333333333333\right)*\left(\left(\text{Crew}-58.3333333333333\right)*0.11522702080284\right)\right)\end{aligned}}$$

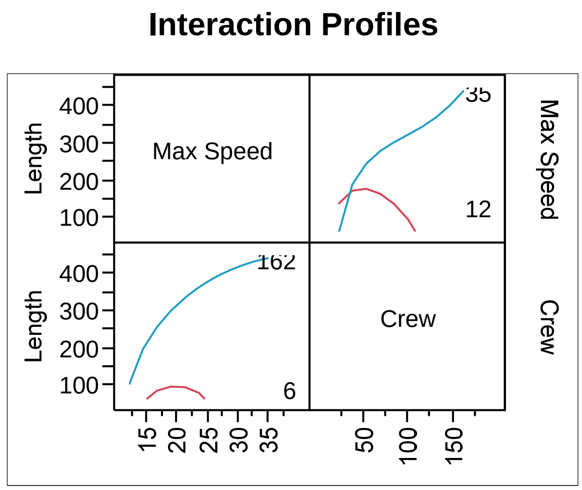


Figure 19. Interaction Profiles for Overall Length

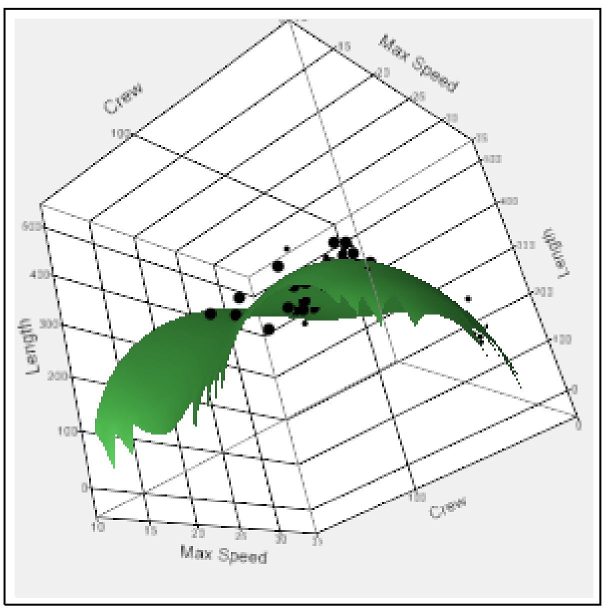


Figure 20. 3D Plot for Overall Length, Crew Complement & Maximum Speed

3. Overall Beam

We modeled Beam, using a stepwise fit, against length. The significant result is beam: = $\sqrt{-445.15208573347 + 7.7456762567854 * Length}$ The output for this regression analysis is depicted in Figures 21 and Table 8.

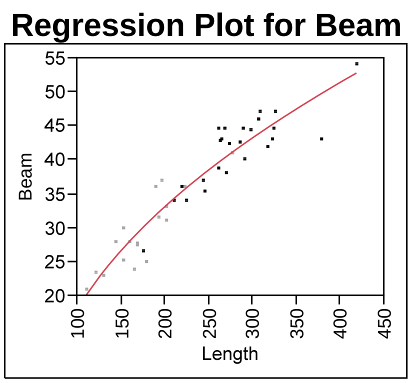


Figure 21. Regression Plot for Overall Beam

Table 8. JMP Regression Output for Overall Beam.

Summary of Fit

RSquare	0.879699
RSquare Adj	0.876901
Root Mean Square Error	203.0922
Mean of Response	1398.878
Observations (or Sum Wgts)	45

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	12969365	12969365	314.4359
Error	43	1773597	41246.451	**Prob > F**
C. Total	44	14742962		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	-445.1521	108.3099	-4.11	0.0002*	-663.5798	-226.7244
Length	7.7456763	0.436811	17.73	<.0001*	6.8647635	8.626589

Prediction Expression

$$\sqrt{-445.15208573347 + 7.7456762567854 * \text{Length}}$$

4. Full Load Displacement

We modeled Full Load Displacement, using a stepwise fit, against Overall Beam. The significant result is: Full Load Displacement = -5734212.6 + 239090(Beam) + $(Beam - 36.5)^2$*4082.5. The output for this regression is depicted in Figures 22 and Table 9.

Regression Plot for Displacement

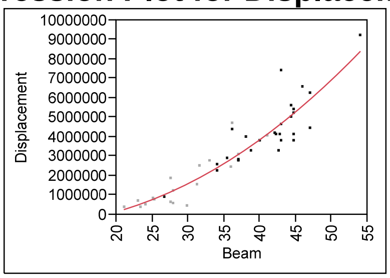


Figure 22. Regression Plot for Full Load Displacement

Table 9. JMP Regression Output for Full Load Displacement.

Summary of Fit

RSquare	0.851564
RSquare Adj	0.844495
Root Mean Square Error	807517.2
Mean of Response	3261942
Observations (or Sum Wgts)	45

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	1.5712e+14	7.856e+13	120.4748
Error	42	2.7388e+13	6.521e+11	**Prob > F**
C. Total	44	1.8451e+14		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	-5734213	610080.2	-9.40	<.0001*	-6965404	-4503021
Beam	239090.06	15427.29	15.50	<.0001*	207956.52	270223.6
(Beam-36.5447)*(Beam-36.5447)	4082.4689	1848.588	2.21	0.0327*	351.86726	7813.0705

Prediction Expression

$$-5734212.6001645 + 239090.063798214 * \text{Beam} + \left(\text{Beam} - 36.5446666666667 \right) * \left(\left(\text{Beam} - 36.5446666666667 \right) * 4082.46888522724 \right)$$

5. Light Ship Weight

We modeled light ship weight, using a stepwise fit, against full load displacement. The significant result is light ship weight = 51006 + .72(Displacement)

Since the majority of the weight data acquired was reported in full load displacement, and since we had already confirmed, through our analysis, that light ship weight and full load displacement are related, we utilized data points that contained both light ship weight and full load displacement and refreddion analysis to model that relationship. In that way we are able to derive light ship weight from the remaining data points that only report full load displacement.

The use of OPVs within a limited range and acquired data is mostly attributed to full load displacement rather than light ship weight. It is necessary to use this estimate to build more light ship weight data points that can strongly represent the variability of OPVs currently in operation. The outputs for this regression analysis is depicted in Figures 23 and Table 10.

An analysis to determine light ship weight was completed on the three points containing both light ship weight and full load displacement and it was evident that although the amount of data was small, light ship weight showed significant relation to full load displacement.

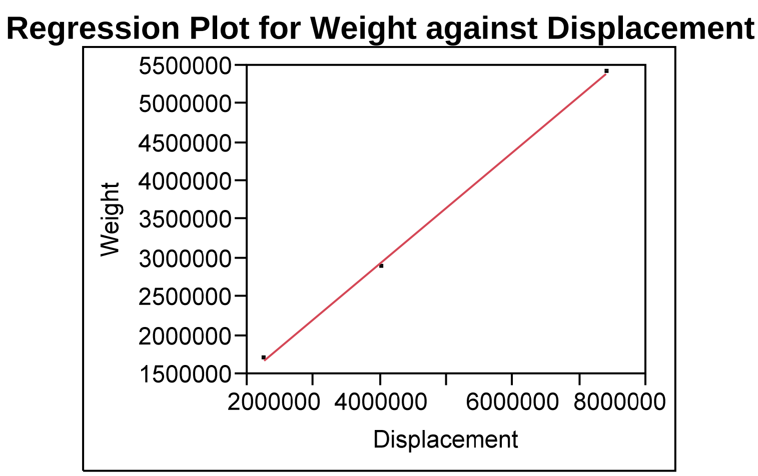


Figure 23. Regression Plot for Weight against Displacement

Table 10. JMP Regression Output for Light Ship Weight

Summary of Fit

Rsquare	0.999412
Rsquare Adj	0.998823
Root Mean Square Error	64826.63
Mean of Response	3340934
Observations (or Sum Wgts)	3

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	7.1391e+12	7.139e+12	1698.783
Error	1	4202491679	4.2025e+9	**Prob > F**
C. Total	2	7.1433e+12		0.0154*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
Intercept	51006.044	88160.27	0.58	0.6661	-1069176	1171188.4
Displacement	0.7228917	0.017539	41.22	0.0154*	0.5000379	0.9457456

Prediction Expression

51006.0439043492
+0.72289170804551*Displacement

E. UTILIZATION OF THE DASHBOARD

A goal of this thesis is to develop a dashboard that quickly displays the changing OPV production cost estimate as a function of combat system configuration and mission dependent combat capabilities. The production cost estimates derived through the use of the cost estimating tool developed for this thesis and for the NPS efforts towards the ASNET/PRONTO simulation analysis that guided the combat system configurations, provided an opportunity to validate the developed cost model by comparing various costs estimates based on these different combat configurations. These cost estimates proved to be a good determinant for future decision making considerations.

The cost model developed for this thesis effort, paired with individual simulation outputs that others at NPS developed in support of ASNET/PRONTO, permit simultaneous linkages across combat system configuration, combat effectiveness and cost estimates. We used the cost estimating model that we developed, and the dashboard within which it is embedded to demonstrate our ability to develop production cost estimates from simulation outputs

In this section we demonstrate the dashboard's costing ability in relation to the simulation outputs done by Royal Thai Navy CDR Peerapong Yoosiri, LT Jason McKeown, and LT Joseph Ashpari. This detailed investigation gives insight into the dashboards utilization abilities.

1. Royal Thai Navy CDR Peerapong's MIO Simulation

CDR Yoosiri Peerapong of the Royal Thai Navy developed a simulation model, complemented with an advanced design of experiments (DOE) approach. His model replicated the simulation efforts from the Italian model's MIO mission and improved upon the research to investigate significant input parameters. These pinpointed more realistic combat attributes that more accurately defined the mission effectiveness. In an effort to explore relationships from his simulation, the utilization of partition platforms in JMP were used to recursively partition the simulation output data in order to investigate relationships. Through this method, the following was determined:

The Italian model representing the MIO mission indicated that the MOE was substantially higher when operating in a small area, and within these small areas, using an OPV with an on-board helicopter increased the MOE. With identification of a 35 to 40 NM area, the MOE increased from 73.4, for an OPV with no on-board helicopter, to 88.6, for an OPV with one on-board helicopter. Considering an OPV that has a max speed of 22kts, the maximum speed considered in both simulation efforts, and that is not complemented with a helicopter would cost on average between 54.35M and 79.61M; whereas an OPV that has a maximum speed of 22kts and is complemented with a helicopter would cost, on average, between 94.38M and 127.93M. Therefore based on the conclusions of the Italian model, a decision maker would have to decide whether spending an extra 40M to 50M per ship would be worth the greater MOE for this mission. All aspects of the ships composed in this analysis via the dashboard are depicted in Table 11, specifically labeled scenario a.

CDR Peerapong's simulation that was used to replicate the Italians' also concluded that in a smaller area an OPV complemented with a helicopter on-board would significantly increase the MOE. His model went a step further by identifying not only a smaller area, but a medium and a larger area. This simulation analysis concluded that hands-down complementing an OPV with an on-board helicopter would increase the MOE of the MIO mission despite the area. It is important to understand the MOE employed by CDR Peerapong's model and the Italian model are both represented on different scales. They share the ability to evaluate for both positive and negative variations; however, they are representative of a similar baseline approach.

In a substantial small area, smaller than the one analyzed in the Italian based model, an MOE goes from 38.8 to 61.2 by including an on-board helicopter. Considering a similar area as mentioned for the Italian model, the MOE goes from 23.3 to 43.5 by including the on-board helicopter and goes from 17.3 to 31.2, respectively, for a really large area.

CDR Peerapong further advanced his simulation to distinguish between using a parallel searching pattern versus a random searching pattern.

He concluded that the significance lied within the size of the area searched when utilizing the parallel searching method; this was complemented by the maximum speed ability of the OPV. For instance in a substantial large area where the proposed armed smuggling boat, represented as a red agent in the MANA simulation as seen in Figure 24, has the max speed capability greater than 26.3kts, an OPV with a max speed less than 33.7kts only has an MOE of 24% whereas an OPV with a max speed above 33.7kts has a MOE of 35%. In order to use these factors to investigate the cost model created for this thesis, the average cost of a ship that has a max speed of 33kts is between 21.78M to 41.37M while a ship that has a max speed of 34kts is between 13.09M to 31.53M. This is explained by the fact that the cost model developed utilizes an average of the propulsion systems based off the 48 ships represented in Jane's Fighting Ships. If max speed is the only issue, then accomplishing the combat effectiveness would simply mean building a smaller ship while utilizing the same engine. This can be seen in Table 11, section b.

In investigating the simulation model using the random search pattern, the analysis showed that the factor of whether to use an OPV with an on-board helicopter was the significant implication from the resulting data. For instance, an OPV that did not have an on-board helicopter had an MOE of 29%, while an OPV with an on-board helicopter had a MOE of 52%. To place this investigation into a deeper perspective, the analysis showed that an OPV without an on-board helicopter and having the capability of a max speed less than 32.9kts that was trying to interdict a red agent that had a max speed greater than 25kts, resulted in a MOE of 17%, while a non-helicopter OPV that had the max speed capability above 32.9kts has an MOE of 32%. In cost estimation perspectives, a non-helicopter OPV that has a max speed of 32kts would have an average cost based between 28.33M to 49.09M while a non-helicopter OPV that has a max speed capability of 33kts would have an average cost between 21.78M to 41.37M. Once more we have the opportunity to show that having a greater maximum speed relies on a smaller ship with the same engine, thus being more cost effective while increasing the MOE of the MIO mission from this simulation effort. This can be seen in Table 11, section c. Although a deeper investigation into the cost model will show that by increasing the maximum speed capabilities once you add various combinations of armament and on-board flight capabilities, the rate of the cost decrease goes dramatically down, perhaps reflecting the saddle point represented in Figure 20.

CDR Peerapong further advanced his MIO simulation to include the use of an on-bard VUAV. The cost model was designed with the capability for OPV architectural parameter changes based on including up to four VUAVs on-board. The analysis of CDR Peerapong's advanced MIO simulation showed there would be a significant MOE increase when an OPV has an on-board helicopter and is utilizing a VUAV in a very large area. This analysis was further pinpointed to represent operations where the "red target" could not achieve a maximum speed over 36.3kts. Within this design and these constraints a 1-helicopter OPV that had the capability to travel 22kts without the additional VUAV performed with a 43% MOE while the same OPV that had the advantage of the additional on-board VUAV performed with a 67% MOE. A 1-helicopter OPV with a max speed of 22kts w/o an on-board VUAV costs between 85.23M to 115.53M with an external cost of 31M for the helicopter while the same OPV with the advantage of the on-board VUAV would range from 87.83M to 118.63M with the external cost of 42.2M for the VUAV and Helicopter. This can be seen below in Table 11, section d

Table 11. Cost Estimates for MIO Simulation Output Analysis

Royal Thai Navy Yoosiri Peerapong's Production Cost Estimates based on his MIO Simulation output																			
					T1 (FY12$M)			Average Cost (4 ships in production) (FY12$M)			Average External Cost per Ship (FY12$M)				Architectural Estimates				
Scenario	option	On-Board Helicopter(s)	On-Board VUAV(s)	Max Speed	Lower 80% CI	Estimate	Upper 80% CI	Lower 80% CI	Estimate	Upper 80% CI	Helo(s)	VUAV(s)	Missile(s)	Total Avg External Costs	Overall Length (ft)	Overall Beam (ft)	Full Load Displacement (lbs)	Average Crew Complement
a	1	0		22	60.17	75.4	88.14	54.35	68.1	79.61	0	0		0	223	36	2820000	27
a	2	1		22	94.38	112.4	127.93	85.23	101.5	115.53	31	0		31	278	41	4240000	62
b	3	0		33	24.09	36.5	45.76	21.78	33	41.37	0	0		0	162	28	1330000	27
b	4	0		34	15.17	26.8	34.91	13.69	24.2	31.53	0	0		0	146	26	960000	27
c	5	0		32	31.37	44.3	54.37	28.33	40	49.09	0	0		0	175	30	1630000	27
c	3	0		33	24.09	36.5	45.76	21.78	33	41.37	0	0		0	162	28	1330000	27
d	2	1		22	94.38	112.4	127.93	85.23	101.5	115.53	31	0		31	278	41	4240000	62
d	6	1	1	22	97.25	115.6	131.36	87.83	104.4	118.63	31	11.2		42.2	283	42	4360000	80

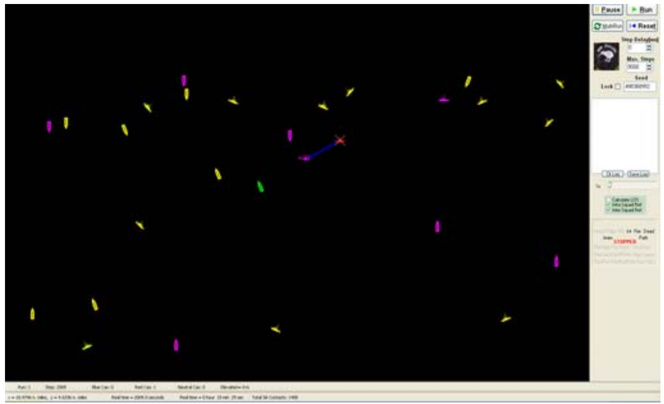


Figure 24. Royal Thai Navy CDR Peerapong's MANA Simulation—depicting a screenshot of the end-state of a scenario model (Y. Peerapong, Thesis pending publishing, June 2012).

2. LT Joe Ashpari of the United States Navy

LT Joe Ashpari developed a SAR model that investigated combinations involving the use of a ships maximum speed capability, the employment of on-board medium sized helicopters, and the use of on-board VUAVs. Other noise factors represented in LT Ashpari's model included: ship search speed, wind speed, datum uncertainty, initial distance of ship to target, type of search target, environmental control factors, wind direction, maximum VUAV speed, maximum helicopter speed, VUAV search speed, and helicopter search speed. This model utilized a DOE method that allowed for the investigation of responses based on the interconnection over a wide range of values. Moreover he was able to compile an analysis that determined the best configuration based on a MOE that defined the time required to identify the given target. His conclusion showed that in order to identify the target in an average time of 2.74 hours, an OPV would require no on-board helicopters and 2 on-board VUAVs along with a capability to travel greater than 8 knots.

With the utilization of the production cost dashboard, it was determined that such an OPV would have an average cost between 37.77M and 60.22M with an average external cost of 22.4 million dollars for the VUAVs. Further consideration would recognize that since the MOE only represents the time to detection and does not represent travel time to rescue the target, there might be a need to increase the maximum speed capability of the OPV. The initial cost estimation was done in consideration of achieving an estimate of an OPV with 2 VUAVs and a maximum speed capability greater than 8kts. Through means of the utilizing the cost model it was determined that the lowest possible maximum speed for an OPV capable of deploying 2 on-board VUAVs was 13kts. Increasing this speed would likewise increase the production cost estimation. For example a 2-VUAV OPV with a maximum speed capability of 20kts, which would be a more realistic speed capability, is estimated to have an average cost between 79.10M and 108.45M. Figure 25 depicts this analysis with a line graph showing the growth of architectural design factors and cost estimations as the maximum speed capability of the ship increases.

LT Ashpari further concluded more ships with a growing mean time to detection. Thus utilizing the OPV as a platform to launch and retrieve VUAVs and without using speed as a factor would not require extreme costs based on the cost analysis of the historical comparisons. Given the understanding that a VUAV is not able to retrieve a person in a SAR situation, yet a helicopter is would be another factor to be further analyzed by decision makers. A decision maker can utilize the cost estimates to decide whether it is more appealing to design an OPV capable of detecting a SAR target really quickly and has maximum speed capabilities to sail to its target or whether it is more beneficial to design an OPV capable of deploying a helicopter and VUAV for a higher cost, yet having the ability to interact with a SAR target in a more efficient timely manner. Table 12 shows the cost comparisons based on LT Ashpari's model.

Table 12. Cost Estimates for SAR Simulation Output Analysis

LT Joseph Ashpari's Production Cost Estimates based on his SAR Simulation output																					
			Missile System					T1 (FY12$M)			Average Cost (4 ships in production) (FY12$M)			Average External Cost per Ship (FY12$M)				Architectural Estimates			
Mean Time (hrs)	On-Board Helicopter(s)	On-Board VUAV(s)	Marte	Exocet	Max Speed	Helicopter in AO	30mm Gun System	Lower 80% CI	Estimate	Upper 80% CI	Lower 80% CI	Estimate	Upper 80% CI	Helo(s)	VUAV(s)	Missile(s)	Total Avg External Costs	Overall Length (ft)	Overall Beam (ft)	Full Load Displacement (lbs)	Average Crew Complemen
2.74	0	2			13			41.76	55.5	66.58	37.77	50.2	60.22	0	22.4		22.4	192	32	2060000	
2.74	0	2			16			66.45	82.2	95.49	59.98	74.2	86.2	0	22.4		22.4	233	37	3080000	
2.74	0	2			20			87.6	105.1	120.1	79.1	94.9	108.45	0	22.4		22.4	267	40	3960000	
2.74	0	2			22			94.38	112.4	127.93	85.23	101.5	115.53	0	22.4		22.4	278	41	4240000	
2.99	1	2			30			121.98	142.2	159.99	110.14	128.4	144.46	31	22.4		53.4	321	45	5380000	
4.68	0	1			12			34.35	47.5	57.87	31.02	42.9	52.26	0	11.2		11.2	180	31	1750000	
5.1	1	2			31			122.8	143.2	161.08	111.04	129.4	145.55	31	22.4		53.4	323	45	5420000	
6.92	1	1			21			92.97	110.9	126.33	83.92	100.1	114.03	31	11.2		42.2	276	41	4180000	
7.66	1	2			23			102.26	121	137.15	92.37	109.3	123.89	31	22.4		53.4	291	43	4570000	
15.56	2	0			23			102.14	120.8	136.96	92.25	109.1	123.7	62	0		62	291	42	4560000	
19.2	1	0			13			41.76	55.5	66.58	37.7	50.2	60.22	31	0		31	182	32	2060000	
25.36	0	0			13			28.67	41.5	51.24	25.84	37.4	46.17	0	0		0	170	30	1520000	

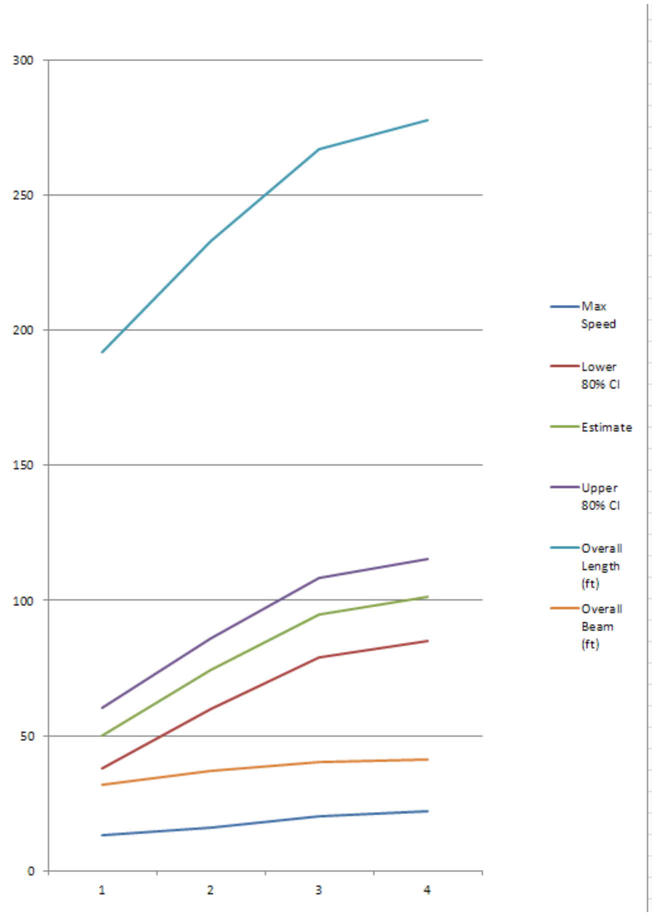


Figure 25. Line graph of various architectural factors and cost estimates of an OPV with 2 on-board VUAVs as Max Speed Capability goes up.

3. LT Jason McKeown of the United States Navy

LT Jason McKeown developed an ASuW model that investigated combinations involving the use of a ships maximum speed capability, various armament configurations and the availability of a medium sized assisting helicopter in the AO. His model replicated the simulation efforts from the Italian model's MIO mission and then sought out to improve upon the research to investigate other significant input parameters. These pinpointed more realistic combat attributes that more accurately defined the mission effectiveness. In an effort to explore relationships from his simulation, the utilization of partition platforms in JMP were used to recursively partition the simulation output data in order to investigate relationships.

The most significant factor in both LT McKeow's ASuW simulation models and the Italian base model simulation of ASuW was the employment of a 35mm gun system. The second most critical factor was the utilization of missiles. Particularly whether the OPV which was already established with a 35mm gun system, also had a higher payload missile system, i.e., Marte vs Exocet. All cost estimates for this effort were computed using OPVs with the maximum speed capability of 22 kts and 4 missiles for scenarios were missiles were employed.

For the Italian Model this was recognized with a MOE that increased from 19.5 for an OPV with less than a 35mm gun system and only having Marte missiles to an MOE of 30 for an OPV with less than a 35mm Gun System with Exocet missiles. An OPV with a 35mm gun system that utilized Marte missiles portrayed an MOE of 69.7 while a OPV that had a 35mm gun system and employed Exocet missiles had a MOE of 82.

Similarily, LT McKeown's model portrayed a growing MOE as more powerful armament was proposed in the model. Starting with an MOE of 25.1 for an OPV with less than a 35mm gun system and Marte Missiles to 47 for an OPV with less than a 35mm gun system and Exocet Missiles. Further the MOE grew from 78.1 for an OPV with a 35mm gun system employing Marte Missiles to 88.5 for an OPV with a 35mm gun system employing Exocet missiles. Although the determination was not fully analyzed as the specific time this thesis was being written, verbal confirmation was given that both the Italian model and LT McKeown’s model showed a significant growing MOE based on the presence of a supporting mid-sized helicopter in the AO. The addition of a mid-sized helicopter in the AO would not change the architectural parameters of the ship but is estimated to cost, on average, 31 million dollars per helicopter (Jane’s All The World’s Aircraft, 2011). Table 13 depicts the production cost estimates for LT McKeown’s ASuW simulation output.

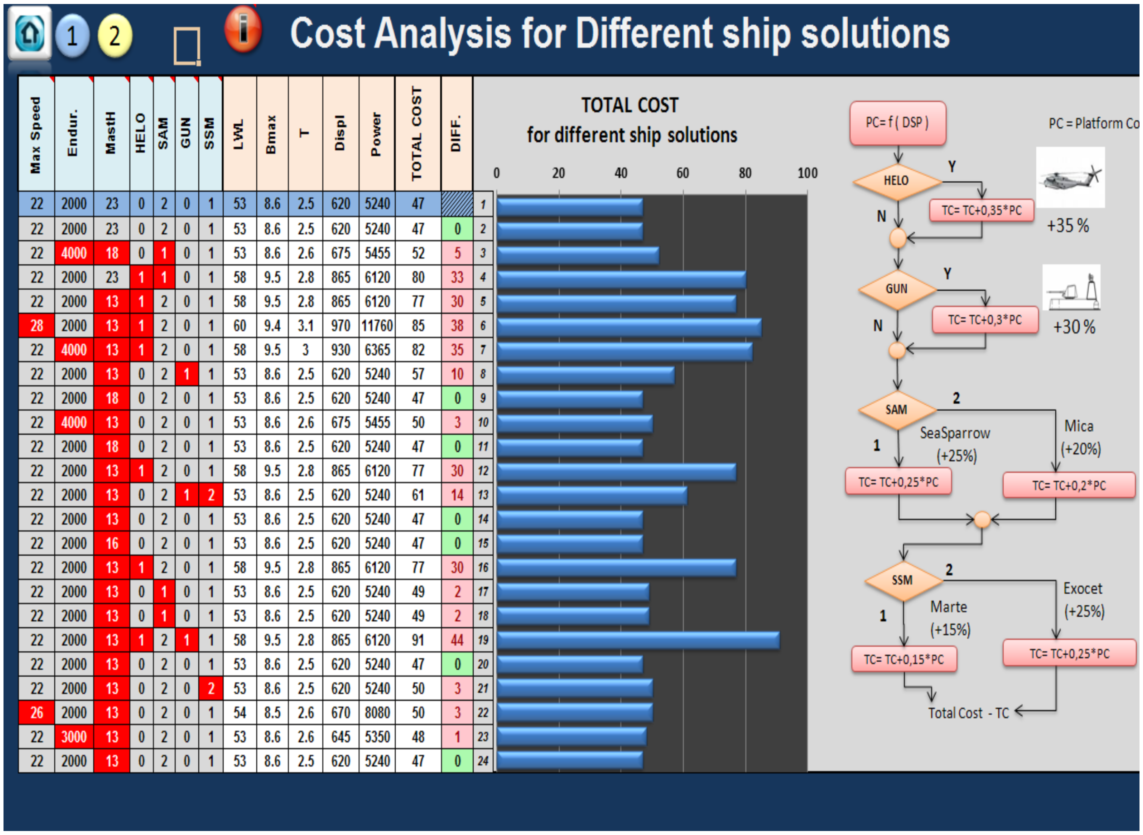
Table 13. Cost Estimates for ASuW Simulation Output Analysis

		Missile System					T1 (FY12$M)			Average Cost (4 ships in production) (FY12$M)			Average External Cost per Ship (FY12$M)				Architectural Estimates			
On-Board Helicopter(s)	On-Board VUAV(s)	Marte	Exocet	Max Speed	Helicopter in AO	30mm Gun System	Lower 80% CI	Estimate	Upper 80% CI	Lower 80% CI	Estimate	Upper 80% CI	Helo(s)	35MM	Missile(s)	Total Avg External Costs	Overall Length (ft)	Overall Beam (ft)	Full Load Displacement (lbs)	Average Crew Complement
		4	0	22	0	0	73.34	89.7	103.53	66.23	81	89.49			2.4	2.4	244	38	3370000	35
		0	4	22	0	0	82.51	99.6	114.18	74.56	90	103.18			4.8	4.8	259	40	3750000	35
		0	0	22	0	1	74.55	91	104.93	67.34	82.2	94.78		0.35		0.35	246	38	3420000	36
		4	0	22	0	1	83.5	100.7	115.39	75.37	90.9	104.16		0.35	2.4	2.75	261	40	3790000	44
		0	4	22	0	1	89.49	107.2	122.32	80.81	96.8	110.46		0.35	4.8	5.15	271	41	4040000	52

F. COMPARATIVE ANALYSIS

We examined the Italian model and their cost analysis, in order to understand it and to compare it to what we developed. The Italian model uses Length at Waterline (LWL), Breadth (Bmax), Draught (T), Displacement (Displ), Power. Their cost estimates are in millions of euros, without giving any specific FY These variable are different from the ones we used in this thesis, namely Crew Complement, Overall Length(ft), Overall Beam(ft), Full Load Displacement(lbs), Light Ship Weight(lbs), and cost in US FY12$M.

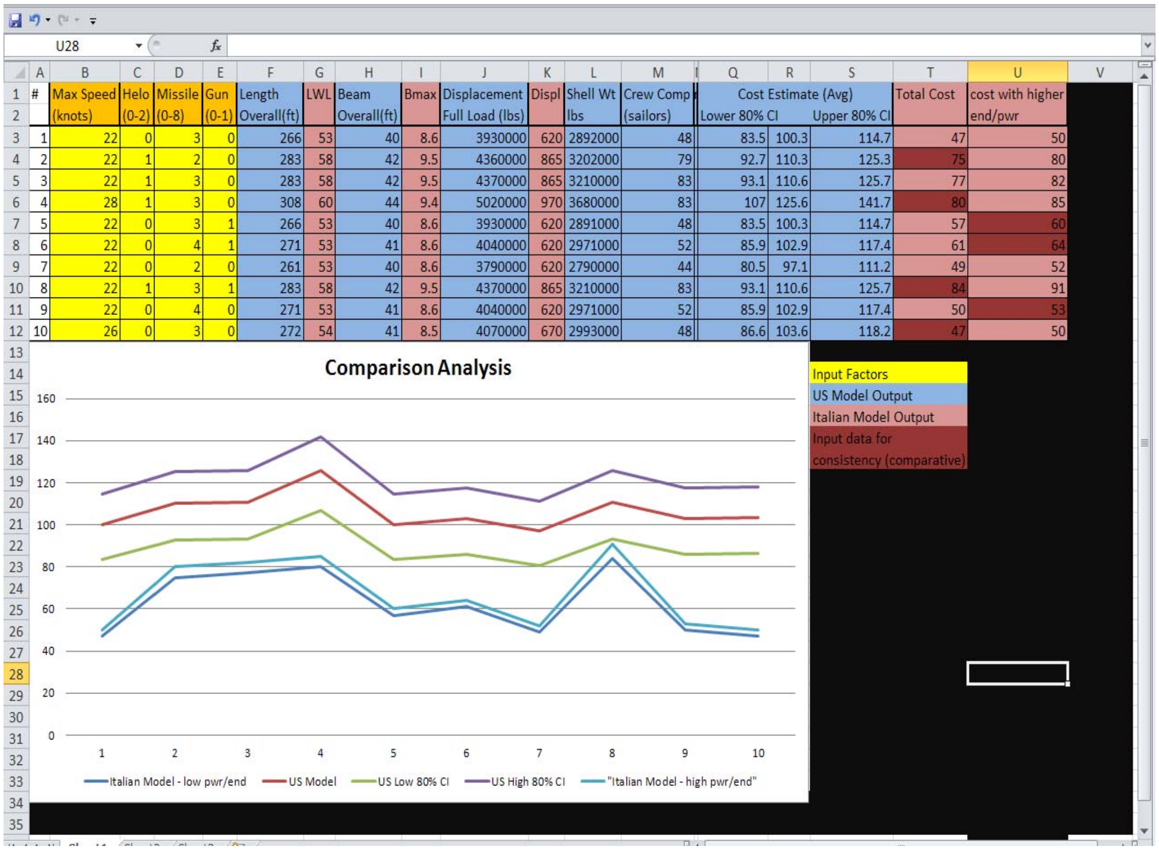
The Italian model cost analysis is depicted in Figure 26.



Max Speed	Endur.	MastH	HELO	SAM	GUN	SSM	LWL	Bmax	T	Displ	Power	TOTAL COST	DIFF.	
22	2000	23	0	2	0	1	53	8.6	2.5	620	5240	47		1
22	2000	23	0	2	0	1	53	8.6	2.5	620	5240	47	0	2
22	4000	18	0	1	0	1	53	8.6	2.6	675	5455	52	5	3
22	2000	23	1	1	0	1	58	9.5	2.8	865	6120	80	33	4
22	2000	13	1	2	0	1	58	9.5	2.8	865	6120	77	30	5
28	2000	13	1	2	0	1	60	9.4	3.1	970	11760	85	38	6
22	4000	13	1	2	0	1	58	9.5	3	930	6365	82	35	7
22	2000	13	0	2	1	1	53	8.6	2.5	620	5240	57	10	8
22	2000	18	0	2	0	1	53	8.6	2.5	620	5240	47	0	9
22	4000	13	0	2	0	1	53	8.6	2.6	675	5455	50	3	10
22	2000	18	0	2	0	1	53	8.6	2.5	620	5240	47	0	11
22	2000	13	1	2	0	1	58	9.5	2.8	865	6120	77	30	12
22	2000	13	0	2	1	2	53	8.6	2.5	620	5240	61	14	13
22	2000	13	0	2	0	1	53	8.6	2.5	620	5240	47	0	14
22	2000	16	0	2	0	1	53	8.6	2.5	620	5240	47	0	15
22	2000	13	1	2	0	1	58	9.5	2.8	865	6120	77	30	16
22	2000	13	0	1	0	1	53	8.6	2.5	620	5240	49	2	17
22	2000	13	0	1	0	1	53	8.6	2.5	620	5240	49	2	18
22	2000	13	1	2	1	1	58	9.5	2.8	865	6120	91	44	19
22	2000	13	0	2	0	1	53	8.6	2.5	620	5240	47	0	20
22	2000	13	0	2	0	2	53	8.6	2.5	620	5240	50	3	21
26	2000	13	0	2	0	1	54	8.5	2.6	670	8080	50	3	22
22	3000	13	0	2	0	1	53	8.6	2.6	645	5350	48	1	23
22	2000	13	0	2	0	1	53	8.6	2.5	620	5240	47	0	24

Figure 26. Italian Model Output: Cost Analysis for Different ship solutions (A. Bonvicini, unpublished slide, 2011).

We compared the factors of max speed, the option of an on-board helicopter, the armament option of having missiles and a 35mm gun system. Missing data between normal endurance and high endurance was generated based on averages representative of the available cost data. A difference of 3 million euros was initiated for ships that had costs between 47 and 75 million euros, that difference went up to 5 million euros for ships between 76 and 83 million euros, this difference became further spread to 7 million euros for ships at 84 million euros or greater. Figure 27 depicts the comparison data that was generated comparing the Italian base model against production cost estimates using the cost model developed for this thesis. The red line represents the cost estimate utilizing the model generated for this thesis, while the purple line and green line represent the upper and lower 80% CI, respectively. The light blue line represents the Italian model cost estimates that are composed of ships with higher power components, while the dark blue line represents the ships with lower power components.



#	Max Speed (knots)	Helo (0-2)	Missile (0-8)	Gun (0-1)	Length Overall(ft)	LWL	Beam Overall(ft)	Bmax	Displacement Full Load (lbs)	Displ	Shell Wt lbs	Crew Comp (sailors)	Cost Estimate (Avg) Lower 80% CI		Upper 80% CI	Total Cost	cost with higher end/pwr
1	22	0	3	0	266	53	40	8.6	3930000	620	2892000	48	83.5	100.3	114.7	47	50
2	22	1	2	0	283	58	42	9.5	4360000	865	3202000	79	92.7	110.3	125.3	75	80
3	22	1	3	0	283	58	42	9.5	4370000	865	3210000	83	93.1	110.6	125.7	77	82
4	28	1	3	0	308	60	44	9.4	5020000	970	3680000	83	107	125.6	141.7	80	85
5	22	0	3	1	266	53	40	8.6	3930000	620	2891000	48	83.5	100.3	114.7	57	60
6	22	0	4	1	271	53	41	8.6	4040000	620	2971000	52	85.9	102.9	117.4	61	64
7	22	0	2	0	261	53	40	8.6	3790000	620	2790000	44	80.5	97.1	111.2	49	52
8	22	1	3	1	283	58	42	9.5	4370000	865	3210000	83	93.1	110.6	125.7	84	91
9	22	0	4	0	271	53	41	8.6	4040000	620	2971000	52	85.9	102.9	117.4	50	53
10	26	0	3	0	272	54	41	8.5	4070000	670	2993000	48	86.6	103.6	118.2	47	50

Figure 27. Comparison Graph representing US Cost model against Italian Cost model.

V. SUMMARY AND CONCLUSION

In this chapter we summarize the use of the cost model as it applies to the NICOP initiative. We also describe the framework and how to apply it to future MBSE designs. Finally, we provide ideas for improvements to the cost estimating model and possibilities for future work.

A. UTILIZATION IN NICOP INITIATIVE

The cost model supports the NICOP initiative by providing cost estimates of ship designs that come from the simulation models. These cost estimates allowed for further investigation of MBSE designs within the tradespace of the MBSE paradigm.

B. THE COST MODEL FRAMEWORK

We have succeeded in developing cost estimates which are responsive to combat design and naval architecture considerations.

1. How to Apply this to Future MBSE Designs

The work done in this thesis can be applied to future MBSE designs. The steps necessary to do this are:

- Collect data that are from systems that are analogous to the system being investigated.
- Identify links between operational factors and architectural parameters via regression analysis.
- This process, outlining the steps to achieve this framework, is depicted in Figure 28. The steps to achieve this include:
    - ✓ Identify the factors that define the operational requirements of the system
    - ✓ Identify the factors that affect the architectural engineering of the system
    - ✓ Identify systems analogous to what you are developing
    - ✓ Discover the links from cost to architectural design parameters

- ✓ Utilize Regression Analysis, Analogy, and Expert Judgment to determine these links.
- ✓ Link architectural design parameters to operational requirement factors
- ✓ Utilizing Regression Analysis as well as other analysis methods that best represent the flow from one attribute to the other.

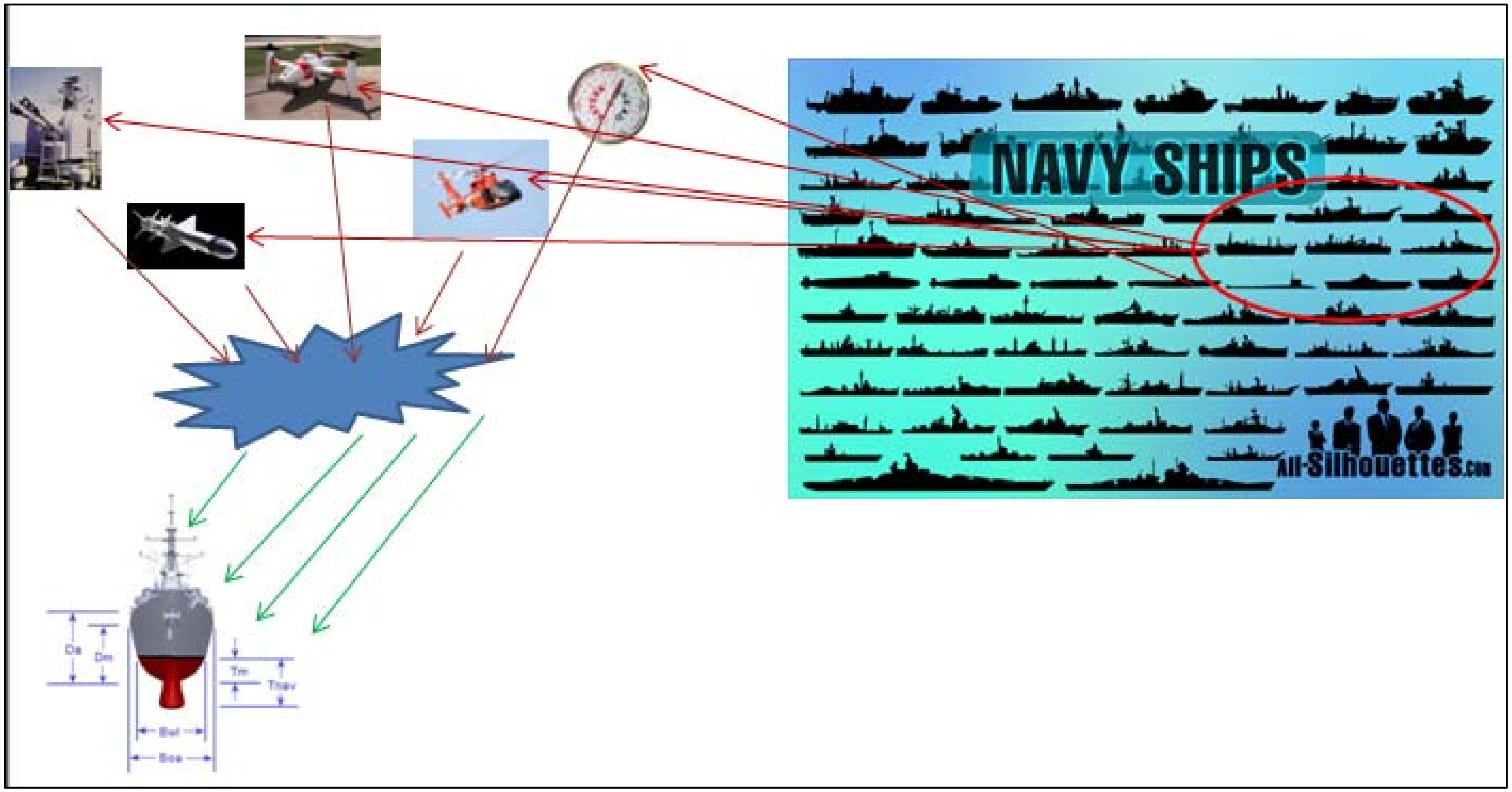


Figure 28. Depiction of the process flow in developing a MBSE production cost model that changes reflective to changes in combat configurations. (Images from (left to right): navweaps.com, surbrook.devermore.net, mnvdet.com, en.wikipedia.org, military-pilots.blogspot.com, 123rf.com, & all-silhouettes.com).

C. IMPROVEMENTS FOR BETTER ANALYSIS

Research projects necessarily have time constraints, data constraints, and associated design constraints, all of which impacted this thesis. Areas for future improvement and research include:

1. Propulsion Systems

The investigation into the design components surrounding the propulsion systems was not applied in this study, based on time constraints. The ability to place further emphasis on propulsion attributes would allow for a more precise cost estimate.

2. Hull Material

Investigating the fabrication of the metal used to construct the ship would provide insight into developing a more comprehensive cost estimating model.p.

3. Complexity Models

Ship hull complexity designs were not used in the development of this model. There exist various hulls that stray from the simple single hull construction as well as attributes within the single hull construction that give a deeper understanding into the complexity of the engineering design. This could be applied to a more comprehensive cost model.

D. USING THIS MODEL FOR NEXT SHIP–BIGGER SHIP–POSSIBLY LSDX

We believe this model and its framework could easily be adapted for a bigger ship or even a different system altogether. We would like to place emphasis on the above mentioned recommendations to make this cost estimating process more comprehensive. However, the concept will remain the same. Acquirement of cost data and other LSD data would allow the design to flourish. Identification of the factors that best represent the architectural parameters via regression or distribution analysis would allow for further investigation into a synthesis flow that best represents the design of the ship. Applying cost to this flow via a dollar per pound or other justifiably associated means would allow for a changing cost estimation representative of the design components of the system as a whole.

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